Chesapeake Bay
Submerged Aquatic Vegetation Water Quality and Habitat-Based Requirements and Restoration Targets: A Second Technical Synthesis

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Executive Summary

The loss of submerged aquatic vegetation, or SAV, from shallow waters of Chesapeake Bay, which was first noted in the early 1960s, is a widespread, well-documented problem. Although other factors, such as climatic events and herbicide toxicity, may have contributed to the decline of SAV in the Bay, the primary causes are eutrophication and associated reductions in light availability. The loss of SAV beds are of particular concern because these plants create rich animal habitats that support the growth of diverse fish and invertebrate populations. Similar declines in SAV have been occurring worldwide with increasing frequency during the last several decades. Many of these declines have been attributed to excessive nutrient enrichment and decreases in light availability.

The health and survival of these plant communities in Chesapeake Bay and other coastal waters depend on suitable environmental conditions that define the quality of SAV habitat. These habitats have been characterized previously for Chesapeake Bay using simple models that relate SAV presence to medians of water quality variables. In *Chesapeake Bay Submerged Aquatic Vegetation Habitat Requirements and Restoration Targets: A Technical Synthesis*, published in 1992, SAV habitat requirements were defined in terms of five water quality variables: dissolved inorganic nitrogen, dissolved inorganic phosphorus, water-column light attenuation coefficient, chlorophyll *a* and total suspended solids. These SAV habitat requirements (Table 1, last five columns) have been used in conjunction with data from the Chesapeake Bay Monitoring Program as diagnostic tools to assess progress in restoring habitat quality for SAV growth in Chesapeake Bay. Attempts to use these habitat requirements to predict SAV presence or absence in Chesapeake Bay and elsewhere, however, have met with mixed success.

REVISING THE HABITAT REQUIREMENTS

Although the 1992 SAV habitat requirements have proved useful in factoring SAV restoration into nutrient reduction goal-setting for Chesapeake Bay, the original habitat requirements contain several limitations:

- It is unclear how many of the five requirements must be met to maintain existing SAV beds or establish new ones.
- The requirements ignore leaf surface light attenuation, which can be high enough to restrict SAV growth where there is a high epiphytic and sediment load on the leaf surface.
- There is no way to adjust the water-column light attenuation coefficient (K_d) requirement for variations in tidal range, or to adjust it for different SAV restoration depths.

For these reasons, we undertook this revision of the original habitat requirements.

The principal relationships between water quality conditions and light regimes for growth of SAV are illustrated in Figure 1, which represents an expansion of a similar conceptual diagram presented in the first SAV technical synthesis. Incident light, which is partially reflected at the water surface, is attenuated through the water column above SAV by particulate matter (chlorophyll *a* and total suspended solids), by dissolved organic matter and by water itself. In most estuarine environments, the water-column light attenuation coefficient is dominated by contributions from chlorophyll *a* and total suspended solids. This was the only component of light attenuation considered in the original habitat requirements.

Based on this conceptual model and an extensive review of the scientific literature, the original K_d habitat requirements were validated and reformulated as the "water-column light requirements" (Table 1). The attainment of the water-column light requirements at a particular site can be tested with the new "percent light through water" parameter (PLW), which is calculated from K_d and water-column depth and can be adjusted for both tidal range and varying restoration depths (Figure 2).

Light that reaches SAV leaves also is attenuated by the epiphytic material (i.e., algae, bacteria, detritus and

TABLE 1. Recommended habitat requirements for growth and survival of submerged aquatic vegetation (SAV) in Chesapeake Bay and its tidal tributaries.

		Primary Requirements†	Secondary Requirements** (Diagnostic Tools)				
Salinity Regime#	**SAV Growing Season***	**Minimum Light Requirement (%)**	**Water Column Light Requirement (%)**	**Total Suspended Solids (mg/l)**	**Plankton Chlorophyll-*a* (µg/l)**	**Dissolved Inorganic Nitrogen (mg/l)**	**Dissolved Inorganic Phosphorus (mg/l)**
Tidal Fresh	April-October	>9	>13	<15	<15	—	<0.02
Oligohaline	April-October	>9	>13	<15	<15	—	<0.02
Mesohaline	April-October	>15	>22	<15	<15	<0.15	<0.01
Polyhaline	March-May Sept.-Nov.	>15	<22	<15	<15	<0.15	<0.02

Regions of the estuary defined by salinity regime, where tidal fresh = <0.5 ppt, oligohaline = 0.5-5 ppt, mesohaline = >5-18 ppt and polyhaline = >18 ppt.

* Medians calculated over this growing season should be used to check the attainment of any of these habitat requirements, and raw data collected over this period should be used for statistical tests of attainment (see Chapter VII). For polyhaline areas, the data are combined for the two growing season periods shown.

† Minimum light requirement for SAV survival based on analysis of literature, evaluation of monitoring and research findings and application of models (see Chapters III, V and VII). Use the primary requirement, or minimum light requirement, whenever data are available to calculate percent light at the leaf (PLL) (which requires light attenuation coefficient [K_d] or Secchi depth, dissolved inorganic nitrogen, dissolved inorganic phosphorus and total suspended solids measurements).

**Relationships were derived from statistical analyses of field observations on water quality variables in comparison to SAV distributions at selected sites. The secondary requirements are diagnostic tools used to determine possible reasons for non-attainment of the primary requirement (minimum light requirement). The water-column light requirement can be used as a substitute for the minimum light requirement when data required to calculate PLL are not fully available.

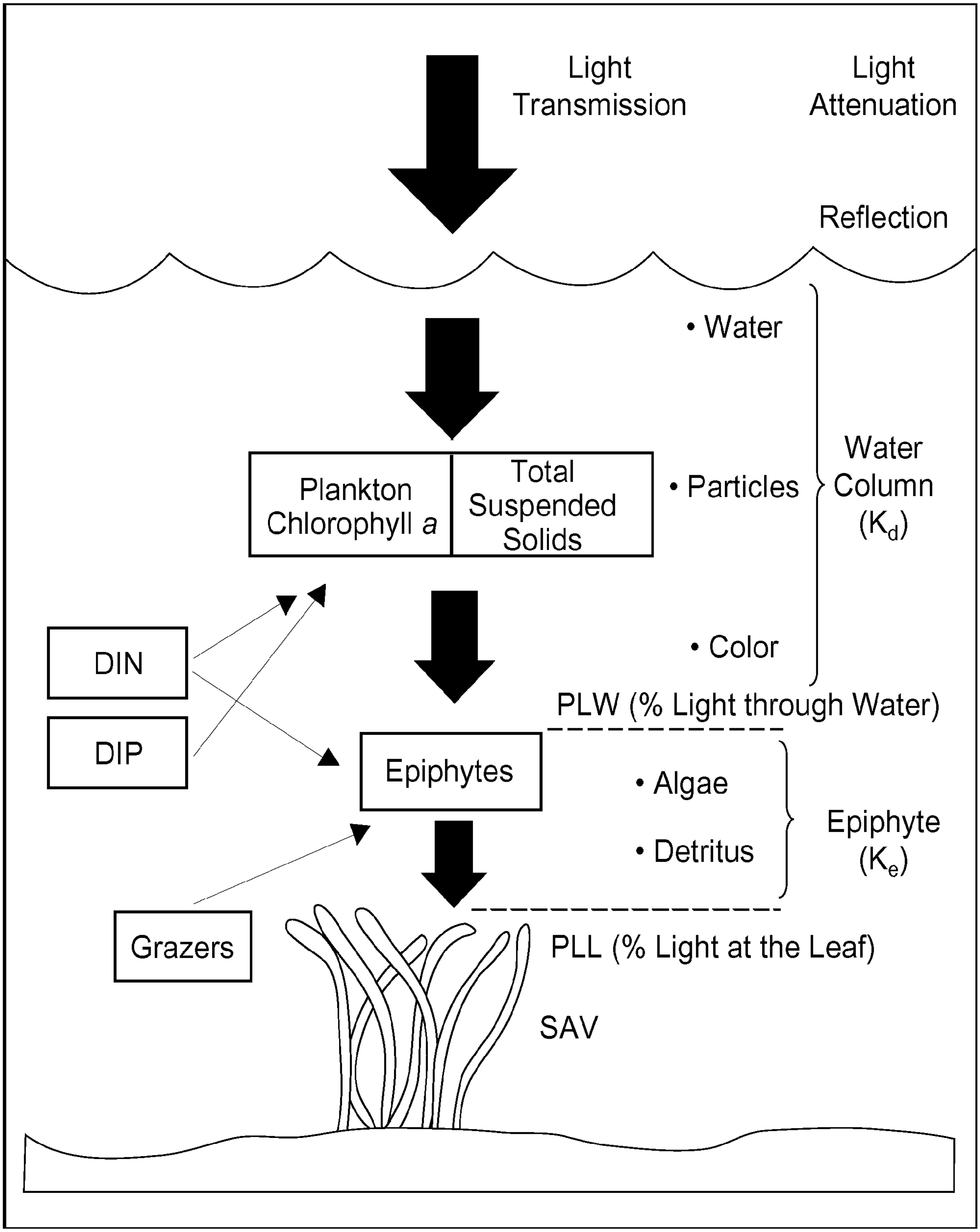

FIGURE 1. Conceptual Model of Light/Nutrient Effects on SAV Habitat. Availability of light for SAV is influenced by water column and at the leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic nitrogen.

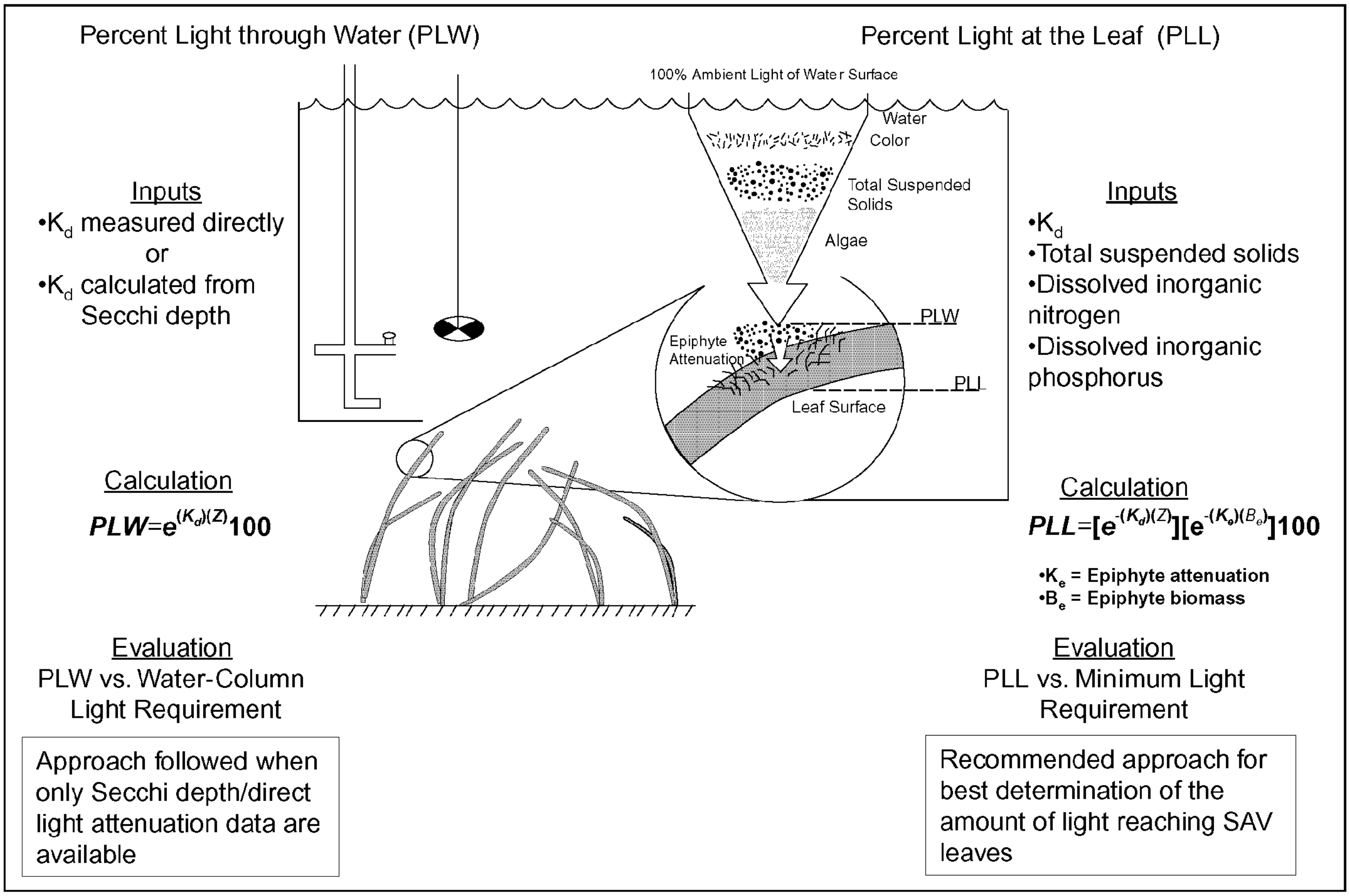

FIGURE 2. Calculation of PLW and PLL and Comparisons with their Respective Light Requirements. Illustration of the inputs, calculation and evaluation of the two percent light parameters: percent light through water and percent light at the leaf.

sediment) that accumulates on the leaves. This epiphytic light attenuation coefficient (called K_e) increases exponentially with epiphyte biomass, where the slope of this relationship depends on the composition of the epiphytic material. Dissolved inorganic nutrients in the water column stimulate growth of epiphytic algae (as well as phytoplankton), and suspended solids can settle onto SAV leaves to become part of the epiphytic matrix. Because epiphytic algae also require light to grow, water depth and K_d constrain epiphyte accumulation on SAV leaves, and light attenuation by epiphytic material depends on the mass of both algae and total suspended solids settling on the leaves. An algorithm was developed to compute the biomass of epiphytic algae and other materials attached to SAV leaves, and to estimate light attenuation associated with these materials. This algorithm uses monitoring data for K_d (or Secchi depth), total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus to calculate the potential contribution of epiphytic materials to total light attenuation for SAV at a particular depth (Figure 2).

The SAV water-column light requirements were largely derived from studies of SAV light requirements, in which epiphyte accumulation on plant leaves was not controlled. Therefore, light measurements in those studies did not account for attenuation due to epiphytes. To determine minimum light requirements at the leaf surface itself, three lines of evidence were compared:

1. Applying the original SAV habitat requirements parameter values to the new algorithm for calculating PLL (Figure 2), for each of the four salinity regimes;
2. Evaluating the results of light requirement studies from areas with few or no epiphytes; and

3. Comparing median field measurements of the amount of light reaching plants' leaves (estimated through the PLL algorithm) along gradients of SAV growth observed within Chesapeake Bay and its tidal tributaries.

Minimum light requirements of 15 percent for mesohaline and polyhaline habitats and 9 percent for tidal fresh and oligohaline habitats resulted from the intersection of these three lines of evidence (Table 1). The attainment of the minimum light requirement at a particular site is tested by comparing it with the calculated PLL parameter (Figure 2).

VALIDATING THE REVISED REQUIREMENTS

The algorithm described above was applied to analyze SAV habitat suitability for some 50 sites in Chesapeake Bay and its tidal tributaries using data collected over 14 years (1985-1998) of environmental monitoring. For each monitoring site, values were calculated for PLW and PLL at 0.5-meter and 1-meter depths, adding half of the tidal range to those values. There was considerable variation in the relationship between PLL and PLW among sites throughout Chesapeake Bay, but clear patterns were evident (Figure 3). Light attenuation by epiphytic material appears to be generally important throughout Chesapeake Bay, contributing 20 to 60 percent additional attenuation (beyond that due to water-column light attenuation) in the tidal fresh and oligohaline regions, where nutrient and total suspended solids concentrations were highest, and contributing 10 to 50 percent in the less turbid mesohaline and polyhaline regions. These findings are consistent with the 30 percent additional light reduction expressed in the PLL value, which was calculated using the 1992 SAV habitat requirements, compared to the PLW parameter value, which was extracted from the same 1992 requirements.

We tested the robustness of this analysis by relating calculated values for PLL at 0.5-meter and 1-meter water depths to SAV presence (over a 10-year record) in areas adjacent to water quality monitoring stations. Five quantitative categories of SAV presence were defined based on SAV areas recorded over all years within the Chesapeake Bay and tidal tributaries' 70 segments. These categories were: always abundant (AA); always some (AS); sometimes none (SN); usually none (UN); and always none (AN). The observed patterns of percent light at the leaf surface versus SAV presence were then compared with the applicable minimum light requirement.

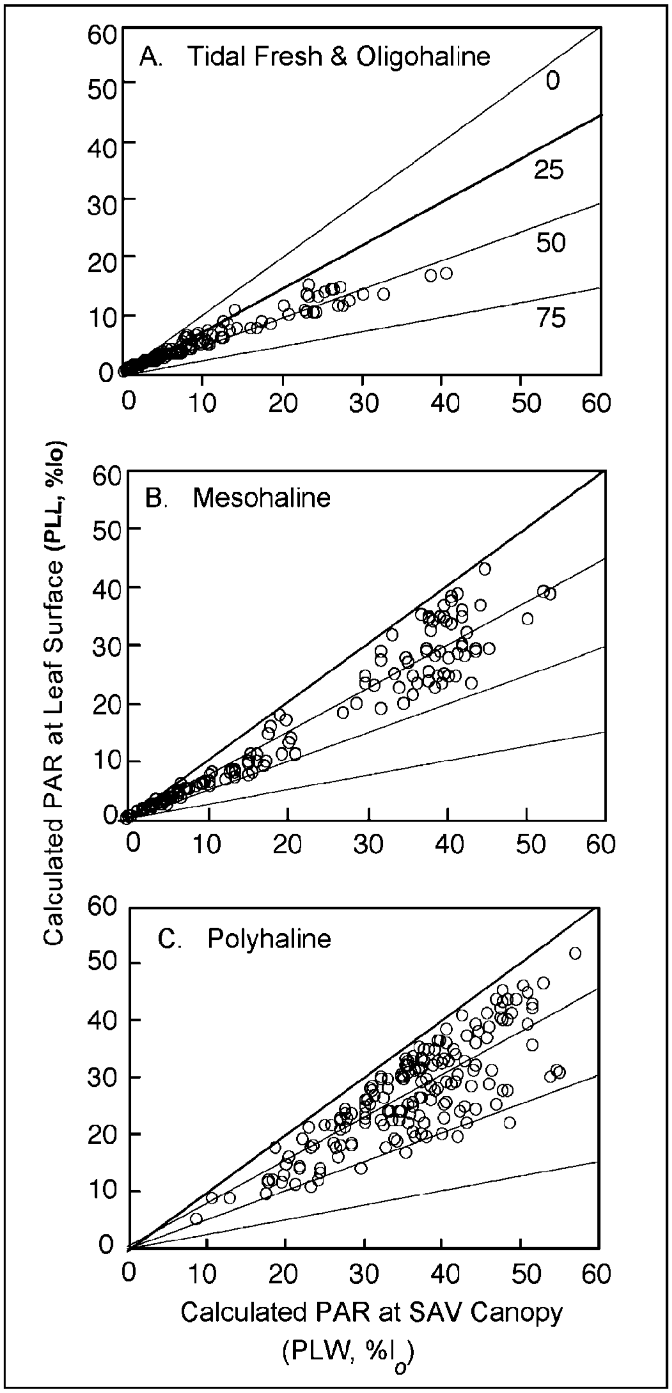

FIGURE 3. Percent Light at Leaf vs. Percent Light Through Water Column by Salinity Regime. Comparing values for percent surface light at SAV leaf surface (PLL) and percent surface light through water just above the SAV leaf (PLW) calculated for Z = 1 m from the model described in this report (Table V-1) for water quality monitoring stations in Virginia portion of Chesapeake Bay for 1985-1996 in three salinity regimes. Lines indicate position of points where epiphyte attenuation reduced ambient light levels at the leaf surface by 0, 25, 50 and 75 percent.

We assumed that water quality adequate to support SAV growth would be found in segments that fell in the AS and SN categories, since they always or usually had mapped SAV. Thus, we predicted that median PLL values for segments in those categories should be near the minimum light requirement. For the mesohaline and polyhaline regions of the Bay, we found excellent agreement (Figure 4) between the median PLL values calculated (at 1-meter depth plus half tidal range) for sites categorized as AS and SN (ranging from 13 to 18 percent) and the minimum light requirement value for these higher salinity areas (15 percent). The agreement was not as close, however, for the tidal fresh and oligohaline regions of the Bay. Median PLL values in these regions ranged from 5 to 8 percent for sites categorized as AS and SN, only exceeding the minimum light requirement value of 9 percent for segments in the AA category at the 0.5-meter restoration depth. For lower salinity segments in the AS or SN categories at the 1-meter restoration depth, the median PLL value was only 1 to 3 percent–far less than the expected 9 percent. SAV species that inhabit shallow waters (0.25 meters or less, even up to the intertidal zone) in the fresh and brackish reaches of the upper Bay and tidal tributaries are predominantly canopy-forming species that grow rapidly until they reach the water's surface. This appears to allow them to grow in low salinity sites where the estimated light level at the leaf at the restoration depth (e.g., 1 meter) is predicted to be inadequate to support SAV growth.

NEW ASSESSMENT AND DIAGNOSTIC CAPABILITIES

An important advancement in this report was the development of an SAV habitat assessment method that explicitly considers water depth requirements for SAV restoration. As SAV is generally excluded from intertidal areas because of physical stress (waves, dessication and freezing), the upper depth-limit for SAV distribution is usually determined by the low tide line. The maximum depth of SAV distribution, in turn, is limited by light penetration. A relatively small tidal range results in a larger SAV depth distribution (Figure 5A), whereas a large tidal range results in a smaller SAV depth distribution (Figure 5B). This is because the upper depth-limit for SAV distribution tends to be lower in areas with larger tidal range. Furthermore, the lower depth-limit tends to be reduced at sites

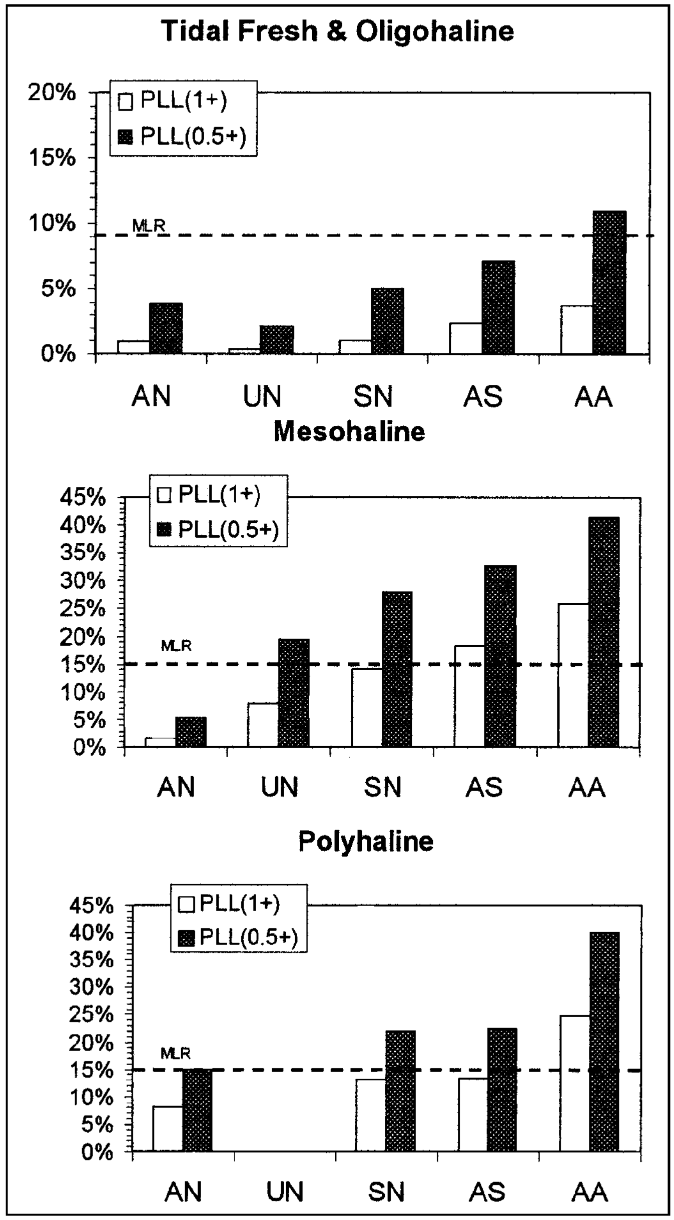

FIGURE 4. Comparison of PLL Values for Different Restoration Depths Across Salinity Regimes by SAV Abundance Category. SAV growing season median percent light at the leaf (PLL) calculated using 1985-1998 Chesapeake Bay Water Quality Monitoring Program data by SAV relative abundance category. AN = Always None, UN = Usually None, SN = Sometimes None, AS = Always Some, AA-Always Abundant. The applicable minimum light requirement (MLR) for each salinity regime is illustrated as a dashed line. The number with a plus symbol within parentheses after PLL indicates the restoration depth adjusted for tidal range.

with larger tidal range because of increased light attenuation through the longer average water column. Thus, there tends to be an inverse relationship between tidal range and the range of SAV depth distribution. When the PLW or PLL parameters are calculated, half the mean diurnal tidal range is added to the target SAV restoration depth value (Z) to reflect this relationship.

A management diagnostic tool was developed for quantifying the attenuation of light within the water column that is attributable to light absorption and scattering by dissolved and suspended substances in water and by water itself. Water-column attenuation of light measured by K_d was divided into contributions from four sources: water, dissolved organic matter, chlorophyll *a* and total suspended solids. The basic relationships were thus described by a series of simple equations, which were combined to produce the equation for the diagnostic tool. The resulting equation calculates linear combinations of chlorophyll *a* and total suspended concentrations that just meet the water-column light requirement for a particular depth (Figure 6) at any site or season in Chesapeake Bay and its tidal tributaries. This diagnostic tool can also be used to consider various management options for improving water quality conditions when the SAV water-column light requirements are not currently met.

This report defines SAV habitat requirements in terms of light availability to support plant photosynthesis, growth and survival. Other physical, geological and chemical factors may, however, preclude SAV from particular sites even when minimum light requirements are met. These effects on SAV are illustrated (Figure 7) as an overlay to the previous conceptualization (Figure 1) depicting interactions between water quality variables and SAV light requirements. Some of these effects operate directly on SAV, while others involve inhibiting SAV/light interactions. Waves and tides alter the light climate by changing the water-column height over which light is attenuated, and by resuspending bottom sediments, thereby increasing total suspended solids and associated light attenuation. Particle sinking and other sedimentological processes alter texture, grain-size distribution and organic content of bottom sediments, which can affect SAV growth by modifying availability of porewater nutrients and by producing reduced sulfur compounds that are phytotoxic. In addition, pesticides and other anthropogenic chemical contaminants tend to inhibit SAV growth. An extensive review of the literature revealed that certain SAV species and functional groups appear to have a limited range in their ability to tolerate selected physical, sedimentological and chemical variables (Table 2).

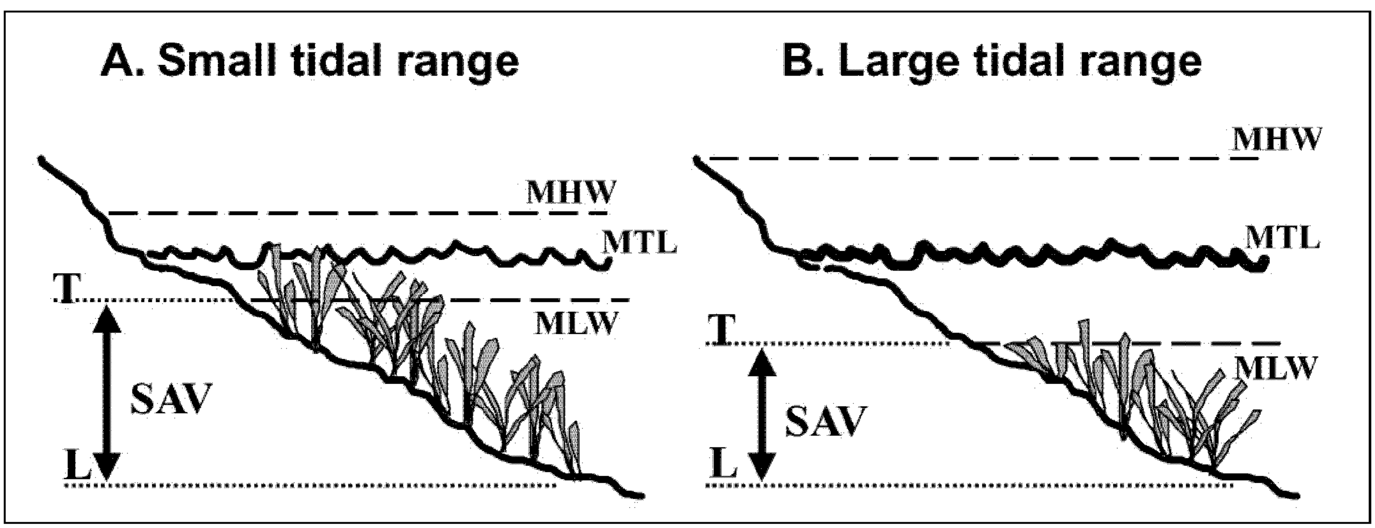

FIGURE 5. Tidal Range Influence on Vertical SAV Depth Distribution. The vertical range of distribution of SAV beds can be reduced with increased tidal range. The minimum depth of SAV distribution (Z_{min}) is limited by the low tide (T), while the maximum depth of SAV distribution (Z_{max}) is limited by light (L). The SAV fringe (arrow) decreases as tidal range increases. A small tidal range results in a large SAV depth distribution (A), whereas a large tidal range results in a small SAV depth distribution (B). Mean high water (MHW), mean tide level (MTL) and mean low water (MLW) are all illustrated.

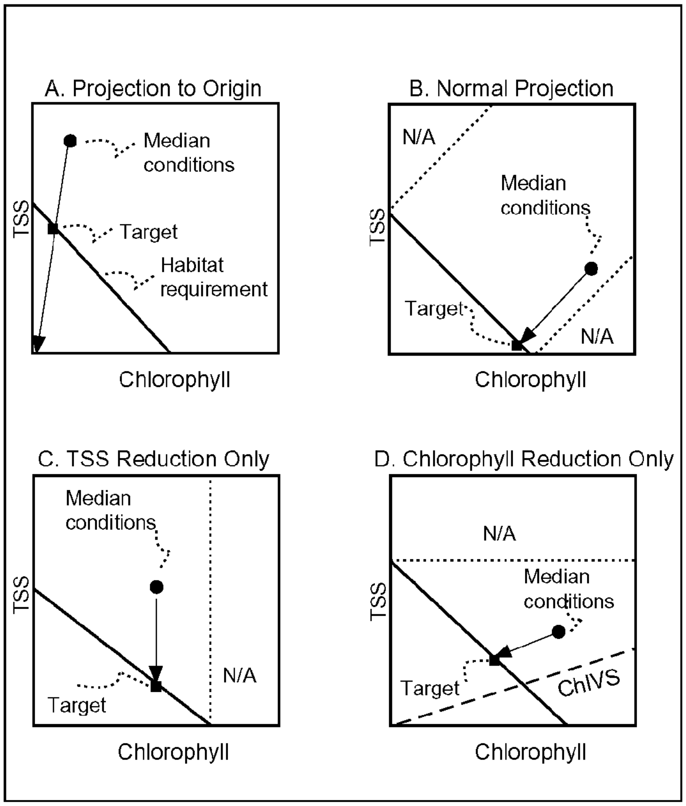

FIGURE 6. Illustration of Management Options for Determining Target Concentrations of Chlorophyll and Total Suspended Solids. Illustration of the use of the diagnostic tool to calculate target growing-season median concentrations of total suspended solids (TSS) and chlorophyll for restoration of SAV to a given depth. Target concentrations are calculated as the intersection of the minimum light habitat requirement, with a line describing the reduction of median chlorophyll and TSS concentrations calculated by one of four strategies: (A) projection to the origin (i.e. chlorophyll=0, TSS=0); (B) normal projection, i.e. perpendicular to the minimum light habitat requirement; (C) reduction in total suspended solids only; and (D) reduction in chlorophyll only. A strategy is not available (N/A) whenever the projection would result in a 'negative concentration'. In (D), reduction in chlorophyll also reduces TSS due to the dry weight of chlorophyll, and therefore moves the median parallel to the line (long dashes) for ChlVS, which describes the minimum contribution of chlorophyll to TSS.

The original tiered SAV distribution restoration targets for Chesapeake Bay, first published in the 1992 SAV technical synthesis, have been refined to reflect improvements in the quality of the underlying aerial survey database and depth contour delineations, based on an expanded baywide bathymetry database (Table 3). The previous targets did not include Tier II, which is potential habitat to 1-meter depth at mean lower low water, because this contour was not available in 1992. As of 1998, baywide SAV distributions covered 56 percent of the areas in the Tier I restoration goal and 16 and 10 percent of the tiers II and III restoration target areas, respectively.

One question raised in the original SAV technical synthesis, which continues to be relevant to this analysis, is the extent to which water quality monitoring data collected from midchannel stations in the Bay and its tidal tributaries represent conditions at nearshore sites where SAV potentially occurs. Several studies conducted by state agencies, academic researchers and citizen monitors since 1992 provided the basis for more comprehensive analysis of this question using data from the upper mainstem Chesapeake Bay and 12 tidal tributary systems. Results revealed that SAV habitat quality conditions are indistinguishable between nearshore and adjacent midchannel stations 90 percent of the time, when station pairs were separated by less than two kilometers.

SUMMARY

The present report provides an integrated approach for defining and testing the suitability of Chesapeake Bay shallow water habitats in terms of the minimum light requirements for SAV survival. It incorporates statistical relationships from monitoring data, field and experimental studies and numerical model computations to produce algorithms that use water quality data for any site to calculate potential light availability at the leaf surface for SAV at any restoration depth. The original technical synthesis defined SAV habitat requirements in terms of five water quality parameters based on field correlations between SAV presence and water quality conditions. In the present approach, these parameters are used to calculate potential light availability at SAV leaves for *any* Chesapeake Bay site. These calculated percent light at the leaf surface values are then compared to minimum light requirements to assess the suitability of a particular site as SAV habitat. Values for the minimum light requirements were derived from algorithm calculations of light at SAV leaves using the 1992 SAV habitat requirements,

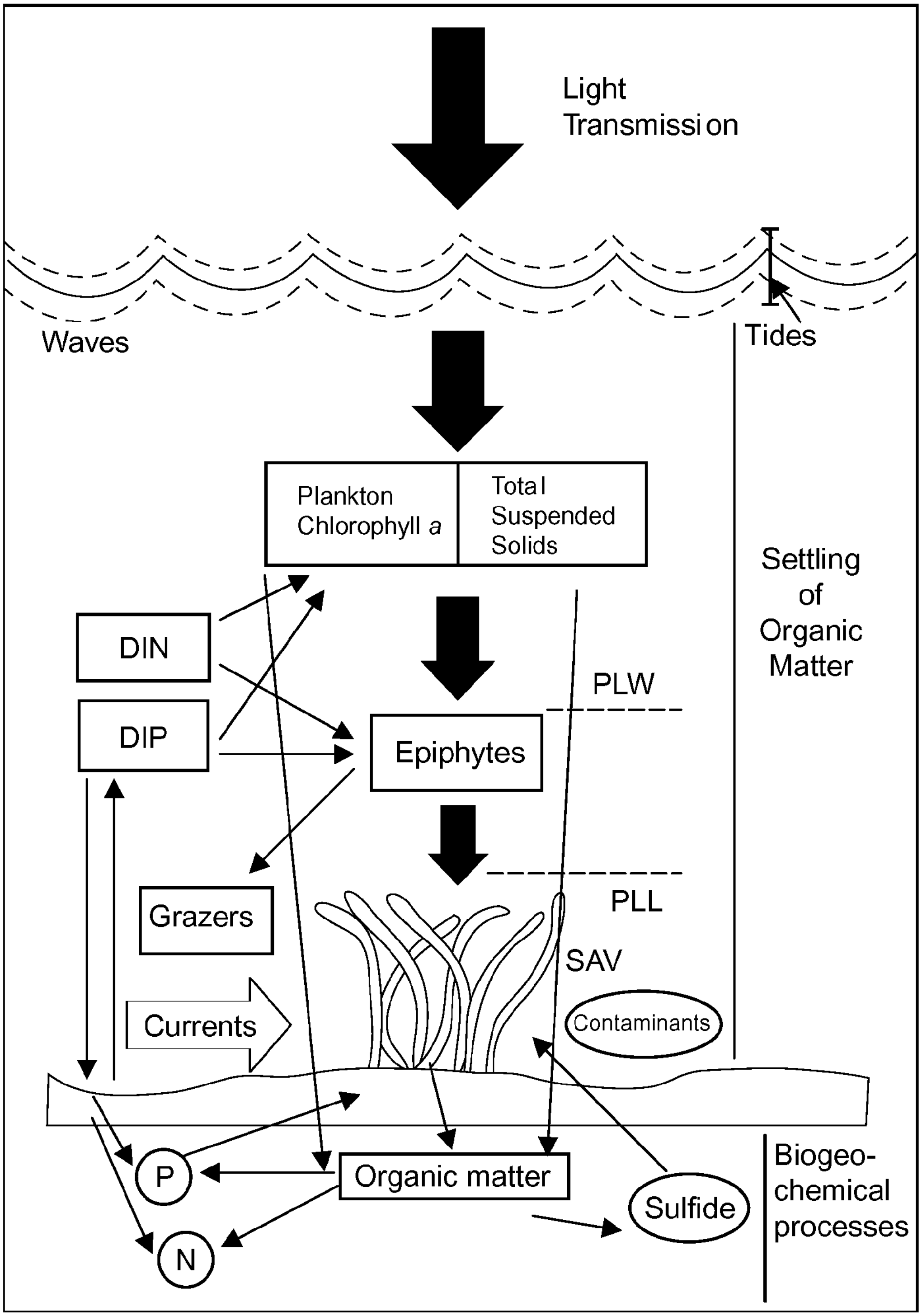

FIGURE 7. Interaction between Light-Based, Physical, Geological and Chemical SAV Habitat Requirements. Interaction between previously established SAV habitat requirements, such as light attenuation, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), chlorophyll a, total suspended solids (TSS) and other physical/chemical parameters discussed in this chapter (waves, currents, tides, sediment organic matter, biogeochemical processes). P = phosphorus; N = nitrogen; PLW = percent light through water; PLL = percent light at the leaf.

TABLE 2. Summary of physical and chemical factors defining habitat constraints for submersed aquatic plants.

Factor	Description	Constraint	Submersed Plants
Water Movement	Minimum velocities ($cm\ s^{-1}$)	0.04-5	Freshwater plants
		3-16	Seagrasses
	Maximum velocities ($cm\ s^{-1}$)	7-50	Freshwater plants
		50-180	Seagrasses
Wave Tolerance	Waves 0-1 m	Limited growth	Canopy formers (e.g., *Myriophyllum spicatum*, *Ruppia maritima* flowers)
	Waves >2 m	Tolerant growth	Meadow formers (e.g., *Zostera marina*, *Vallisneria americana*)
Sediments	Grain size (% fines, <64 µm)	2-62	Freshwater plants
		0.4-30	Seagrasses
	Organic matter (%)	0.4-12	Seagrasses and freshwater plants
Porewater Sulfide	(mM)	<1	Healthy plants
		>1	Reduced growth

TABLE 3. Chesapeake Bay SAV distribution targets and their relationships to the 1998 SAV aerial survey distribution data.

Restoration Target	Description	Area (acres)	1998 SAV Distribution as Percent of Restoration Target
Tier I–composite beds	Restoration of SAV to areas currently or previously inhabited by SAV as mapped through regional and baywide surveys from 1971 to 1990.	113,720	56%
Tier II–one meter	Restoration of SAV to all shallow-water areas delineated as existing or potential SAV habitat down to the one-meter depth, excluding areas identified as unlikely to support SAV based on historical observations, recent survey information and exposure regimes.	408,689	16%
Tier III–two meter	Restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat down to the two-meter contour, excluding areas identified under the Tier II target as unlikely to support SAV as well as several additional areas between one and two meters.	618,773	10%

extensive review of the scientific literature and evaluation of monitoring and field research findings. These calculations account for regionally varying tidal ranges, and they partition total light attenuation into water-column and epiphyte contributions; water-column attenuation is further partitioned into effects of chlorophyll *a*, total suspended solids and dissolved organic matter. This approach is used to predict the presence of suitable water quality conditions for SAV at all monitoring stations around the Bay. These predictions compared well with results of SAV distribution surveys in areas adjacent to water quality monitoring stations in the mesohaline and polyhaline regions, which contain 75 to 80 percent of all recent mapped SAV areas and potential SAV habitat in the Bay and its tidal tributaries.

The approach for assessing SAV habitat conditions described in this report represents a major advance over that presented in 1992. At the same time, areas requiring further research, assessment and understanding have been brought into sharper focus. The key relationships within the algorithm developed for calculating epiphytic contributions to light attenuation can be strengthened and updated with further field and experimental studies. Particular attention needs to be paid to the relationships between epiphyte biomass and nutrient concentrations and between total suspended solids and the total mass of epiphytic material, and to a better understanding of the relationships in lower salinity areas. Detailed field and laboratory studies are needed to develop quantitative, species-specific estimates of minimum light requirements both for the survival of existing SAV beds and for reestablishing SAV into unvegetated sites. Although this report also provides an initial consideration of physical, geological and chemical requirements for SAV habitat, more work is needed to develop integrated quantitative measures of SAV habitat suitability in terms of physical, geological and chemical factors.

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The Chesapeake Bay Program's Living Resources Subcommittee has contributed directly to this second technical synthesis through their funding support of the research needs identified through the 1992 synthesis and continued funding of the annual baywide SAV aerial survey program. This management commitment to funding research supported a second synthesis cycle: synthesis of available data and information; identification of unmet management information needs; funding of required research; continued commitment to long-term monitoring followed by another round of synthesis and management application of new findings.

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Contents

CHAPTER I

Introduction

Underwater grasses, or submerged aquatic vegetation (SAV), represent a conspicuous and important component of shallow estuarine and coastal environments worldwide, because SAV species are keystone species in these ecosystems. Their many roles include providing habitat for juvenile and adult fish and shellfish and protecting them from predators; providing food for waterfowl, fish and mammals; absorbing wave energy and nutrients and producing oxygen; improving water clarity and settling out sediment suspended in the water; and stabilizing bottom sediments. The rich estuarine habitats created by SAV support growth of diverse populations of living estuarine and marine resources.

Health and survival of these plant communities in Chesapeake Bay and other coastal waters depend on maintaining environmental conditions that effectively define the suitable habitat for SAV growth. SAV establishment and continued growth depends principally on light availability but also on several other factors, including the availability of propagules; suitable water quality, salinity, temperature, water depth and tidal range; suitable sediment quality, wave action and current velocity; and low enough levels of physical disturbance and toxic substances.

Suitable SAV habitats were characterized previously for Chesapeake Bay and its tidal tributaries by relating observations of SAV presence or absence to measurements of five water quality variables (Batiuk *et al.* 1992, Dennison *et al.* 1993). This comparative technique was used to define critical levels for dissolved inorganic nitrogen and phosphorus, water column light attenuation coefficient, chlorophyll *a* and total suspended solids. Growing season median values of these water quality parameters were compared at sites classified according to the degree of SAV growth nearby. Habitat requirements for each parameter were chosen that were near the highest (worst) median values found at sites that had SAV growth in each of four salinity regimes. Where growing season median water quality values were lower (better) than these medians, the habitat requirements were met and SAV growth should be possible (although SAV could still be absent from a site with good water quality due to lack of propagules, high wave energy or other causes).

While these five water quality variables relate to many aspects of SAV physiology, their influence on the plant's light climate appears to be of primary importance in determining whether SAV can grow at a site. Attainment of these SAV habitat requirements was used to predict SAV presence or absence at specific sites in Chesapeake Bay and its tidal tributaries (Batiuk *et al.* 1992, Dennison *et al.* 1993) . These predictions were accurate in a majority of cases but several problems remained, especially that of deciding how many of the four or five requirements had to be met to permit SAV growth; how to account for the primacy of the light requirements; and how to explain why some areas had SAV but consistently failed many of the SAV habitat requirements.

In the 10 years since work was first initiated on the first SAV technical synthesis, there have been renewed investments in more focused research, expanded monitoring and ecosystem modeling, prompted, in part, by gaps in understanding that were brought to light after synthesizing the vast quantities of information available through the late 1980s. Prompted by the accumulation of these new data and by insights and advances in ecosystem processes modeling, and driven by management needs for the next generation of habitat requirements, a team of scientists and managers assembled to produce this second technical synthesis.

TECHNICAL SYNTHESIS OBJECTIVES, CONTENT AND STRUCTURE

Synthesis Objectives

The *SAV Technical Synthesis II* has seven major objectives:

1. to establish scientifically defensible minimum light requirements for Chesapeake Bay SAV species;

2. to develop a set of models for determining light availability through the water column and at the leaf surface under a variety of water quality conditions and at varying restoration depths;

3. to provide the management and scientific communities with a set of diagnostic tools necessary to better interpret not only the relative degree of achievement of the light requirements, but also to understand the relative contributions of different water quality parameters to overall light attenuation;

4. to recognize and quantify the many other physical, geochemical and chemical habitat requirements, pointing out the need for further research where the data necessary to develop specific requirements are lacking;

5. to document refinements to the Chesapeake Bay Program's tiered distribution restoration goals and targets;

6. to provide an in-depth assessment of the applicability of midchannel monitoring data for evaluating the water quality in adjacent shallow-water habitats; and

7. to produce a concise list of research needs required to improve our ability to define a holistic picture of habitat quality suitability for SAV.

Synthesis Content and Structure

Interactions among SAV, water quality and physical habitat, which are quantified in the rest of the technical synthesis, are laid out within their respective contexts (Chapter II). Water column-based light requirements for SAV survival and growth are determined through an extensive review of the literature and an evaluation of experimental results from research and monitoring conducted in Chesapeake Bay (Chapter III). The scientific basis for developing diagnostic tools for defining water quality necessary to meet water-column conditions supporting restoration and protection of SAV are documented. This is followed by an illustration of the management applications of the diagnostic tools (Chapter IV). A model is described for calculating light at the leaf surface of plants at given restoration depths under specific water quality conditions (Chapter V). Physical, geological and chemical factors affecting the suitability of a site for SAV survival and growth are discussed with specific quantitative requirements established where supported by scientific data (Chapter VI). Two types of SAV light requirements are defined, along with explanations of how to test their attainment (using two new percent-light parameters calculated from water quality data) and how to account for tidal range. The relationships are tested among the percent-light parameters, SAV area and the average depth at which SAV is growing in Chesapeake Bay (Chapter VII). Refinements to and expansions of the original tiered restoration goals and targets are then documented (Chapter VIII). An expanded, in-depth analysis of midchannel and nearshore water quality measurements is laid out, along with recommendations for site-specific application of midchannel data in characterizing nearshore habitats (Chapter IX). Drawn from the preceding chapters, the technical synthesis concludes with a detailed list of follow-up monitoring and research needed to provide the basis for further quantification of a more expanded set of SAV habitat requirements (Chapter X). The appendices include copies of more extensive tables and methodological documentation referred to within the technical synthesis.

CHAPTER II

SAV, Water Quality and Physical Habitat Relationships

The loss of SAV beds since the early 1960s (Orth and Moore 1983, Kemp *et al.* 1983), primarily because of eutrophication and associated reductions in light availability (e.g., Twilley *et al.* 1985), is of particular concern because these plants create rich animal habitats that support the growth of diverse fish and invertebrate populations (Lubbers *et al.* 1990). They also significantly influence bio-geochemical (e.g., Caffrey and Kemp 1990) and sedimentological (e.g, Ward *et al.* 1984) processes in the estuary. Similar declines in SAV have been occurring worldwide with increasing frequency during the last several decades (e.g., Short and Wyllie-Echeverria 1996), and many of these have been attributed to excessive nutrient enrichment and increases in turbidity (e.g., Cambridge and McComb 1984, Borum 1985, McGlathery 1995, Tomasko *et al.* 1996).

Although the 1992 SAV habitat requirements have proved useful in factoring SAV restoration into nutrient reduction goal-setting for Chesapeake Bay (Chesapeake Executive Council 1993, 1997), a number of serious limitations have been noted in attempting to apply this approach. First, it was unclear how many of the five habitat requirements needed to be met for a particular site to be suitable for maintaining the health of existing SAV beds or for revegetation of denuded sites. Many examples, particularly in the tidal fresh and oligohaline regions of the estuary, have been encountered in which water quality at sites with healthy SAV beds met only three or four of the habitat requirements (Table II-1). On the other hand, in other sites, no SAV was present, despite the fact that most of the habitat requirements were met. An obvious task was to determine which of these variables were most important and how they interacted to define SAV growth requirements. In addition, it was difficult to see how these habitat requirements, as established in the original SAV technical synthesis (Batiuk *et al.* 1992), would be used to accommodate different depth targets for SAV restoration (e.g., 1 meter for Tier II restoration versus 2 meters for Tier III restoration).

Even though light requirements were suggested to be of primary importance for defining SAV habitats with this approach (Dennison *et al.* 1993), explicit relationships between these water quality variables and light availability were, in general, poorly defined (Batiuk *et al.* 1992). The one exception is that light attenuation in the water column can be calculated directly from the exponential coefficient, K_d. In the first SAV technical synthesis, values for K_d, chlorophyll *a* and total suspended solids were set as separate components of the water quality conditions defining SAV habitats, despite the fact that the three variables are highly interdependent (e.g., Gallegos 1994). Finally, there is an implied relationship between SAV habitat requirements for the dissolved inorganic nitrogen and phosphorus concentrations and light attenuation attributable to epiphytic materials on plant leaf surfaces, but this relationship was not explained. In fact, although epiphyte growth and associated light attenuation have been clearly related to estuarine nutrient levels (e.g., Borum 1985, Twilley *et al.* 1985), we are aware of no

TABLE II-1. Comparison of SAV Habitat Requirements with median levels of water quality variables among SAV growth categories within salinity regimes in Chesapeake Bay.

		SAV Habitat Requirements				
		Primary	**Secondary**			
Salinity Regime[#]	**SAV Growth Category In Segment**	**Percent Light at Leaf, 0.5 m (PLL, %)**	**Total Suspended Solids (mg/l)**	**Plankton Chlorophyll-a (ug/l)**	**Dissolved Inorganic Nitrogen (mg/l)**	**Dissolved Inorganic Phosphorus (mg/l)**
Tidal Fresh	**Requirement**	**>9**	**<15**	**<15**	**none**	**<0.02**
	Always Abundant	18	10.0	8.8	0.94	0.006
	Sometimes None	5.6*	20.0*	23.8*	0.66	0.015
	Usually None	1.3	24.0	19.4	1.17	0.033
	Always None	6.6	17.0	7.7**	0.37	0.020
Oligohaline	**Requirement**	**>9**	**<15**	**<15**	**none**	**<0.02**
	Always Abundant	8.5*	17.0*	4.7	0.86	0.047*
	Always Some	7.1*	18.5*	8.7	0.64	0.014
	Sometimes None	4.3*	25.0*	28.7*	0.12	0.005
	Usually None	3.8	27.3	17.4	0.15	0.023
	Always None	2.2	32.8	13.0**	0.23	0.020
Mesohaline	**Requirement**	**>15**	**<15**	**<15**	**<0.15**	**<0.01**
	Always Abundant	41	8.0	8.1	0.08	0.004
	Always Some	33	10.5	9.2	0.11	0.007
	Sometimes None	28	11.0	10.0	0.08	0.005
	Usually None	19**	15.0	15.2	0.09**	0.010
	Always None	5.3	27.0	11.9**	0.18	0.015
Polyhaline	**Requirement**	**>15**	**<15**	**<15**	**<0.15**	**<0.02**
	Always Abundant	40	10.0	6.3	0.05	0.003
	Always Some	22	9.8	5.9	0.12	0.010
	Sometimes None	22	11.1	7.1	0.14	0.015
	Always None	15	11.5**	6.0**	0.21	0.025

* SAV were usually present, even though the habitat requirements were not met (horizontal line is assumed to separate vegetated from unvegetated sites). Note that there are 11 of 50 cases in this category (= 22% disagreement); all of these were in tidal fresh and oligohaline regimes. Dissolved inorganic nitrogen medians were not counted where there was no habitat requirement.

** SAV were usually not present, even though the habitat requirements were met (horizontal line is assumed to separate vegetated from unvegetated sites). Note that there are 7 of 31 cases in this category (= 23% disagreement); there were some in each salinity regime. There are many reasons other than water quality why SAV might be absent, however, including physical conditions and lack of propagules.

quantitative descriptions of such relationships based on field or experimental data. Such relationships can be derived, however, from numerical simulation models, which have successfully described dynamic interactions among nutrients, epiphytic algae, light fields and SAV growth (e.g., Fong and Harwell 1994, Kemp *et al.* 1995, Madden and Kemp 1996, Buzzelli *et al.* 1998).

This report synthesizes new information into a revised approach for establishing SAV habitat requirements for Chesapeake Bay and its tidal tributaries. At the outset, we decided that this revision should focus on how water quality conditions interact to control light available for supporting SAV growth. An additional eight years of monitoring SAV presence and water quality variables at sites throughout the Bay provided a rich data base for further relating SAV occurrence to habitat conditions beyond the original 1992 habitat requirements (Batiuk *et al.* 1992). We used a combination of model simulations and statistical analyses to develop an algorithm that explicitly relates nutrient concentrations and turbidity with epiphyte attenuation of light. The revised approach also develops empirical functions derived from monitoring data to partition the total water-column light attenuation coefficient (K_d) into contributions from phytoplankton biomass, inorganic suspended solids and colored dissolved organic matter. This new approach requires establishing a set of target values of "minimum light requirements" for SAV survival. These are derived from an extensive review of the scientific literature, application of these algorithms to calculate available light under water quality conditions corresponding to the original SAV habitat requirements, and from an evaluation of findings of field water quality conditions along gradients of SAV growth.

The principal relationships between water quality conditions and the light regime for the growth of submersed plants are illustrated in a conceptual diagram (Figure II-1), which represents an expansion from a similar conceptualization presented in the first SAV technical synthesis (Figure 1, Batiuk *et al.* 1992). Incident light, which is partially reflected at the water surface, is attenuated through the water column overlying submersed plants by particulate material (phytoplankton chlorophyll *a* and total suspended solids), by dissolved organic matter and by water itself. In most estuarine environments, water-column attenuation, which is characterized by the composite light attenuation coefficient, K_d, is dominated by contributions from chlorophyll *a* and total suspended solids.

Light is also attenuated by epiphytic material (i.e., algae, bacteria, detritus and sediment) accumulating on SAV leaves. This epiphytic light attenuation is characterized by the coefficient K_e, which increases in linear proportion with increases in the mass of epiphytic material, where the slope of this relationship depends on the composition (e.g, chlorophyll *a*/dry weight) of the epiphytic material. Dissolved inorganic nutrients in the water column stimulate the growth of both phytoplanktonic and epiphytic algae, and suspended solids can settle onto SAV leaves to become part of the epiphytic matrix. Thus, the percent of surface light reaching SAV leaves depends on water depth and on the five water quality variables—dissolved inorganic nitrogen, dissolved inorganic phosphorus, chlorophyll *a*, total suspended solids and water-column light attenuation coefficient—that define the original SAV habitat requirements (Batiuk *et al.* 1992). Because epiphytic algae also require light to grow, water depth and K_d constrain its accumulation on SAV leaves, and light attenuation by epiphytic material (K_e) depends on the mass of both algae and total suspended solids settling on the leaves.

This approach to defining SAV habitat requirements, therefore, explicitly considers water-column depth. Thus, for any site, the minimum water quality conditions needed for SAV growth and survival will tend to vary with depth. Chesapeake Bay and many of its tidal tributaries are characterized by broad shoals flanking a relatively narrow channel, such that relatively large increases in bottom area will accompany small changes in depth-range between 0 to 8 meters (Kemp *et al.* 1999). As a consequence of the estuary's bottom morphology, the doubling of SAV depth penetration from the Tier II (1 meter) to the Tier III (2 meters) distribution restoration targets results in more than a 33 percent increase in potential bottom area of SAV coverage (see Table VIII-1, from 408,689 to 618,773 acres). As of the 1998 aerial survey, however, actual SAV coverage represented only 10 percent and 16 percent of the Tier III and Tier II targets, respectively.

In this report we have used mean tidal level—the mean depth over all tidal cycles during the year—as the reference point from which mean water-column depth is measured. Chesapeake Bay tidal amplitudes

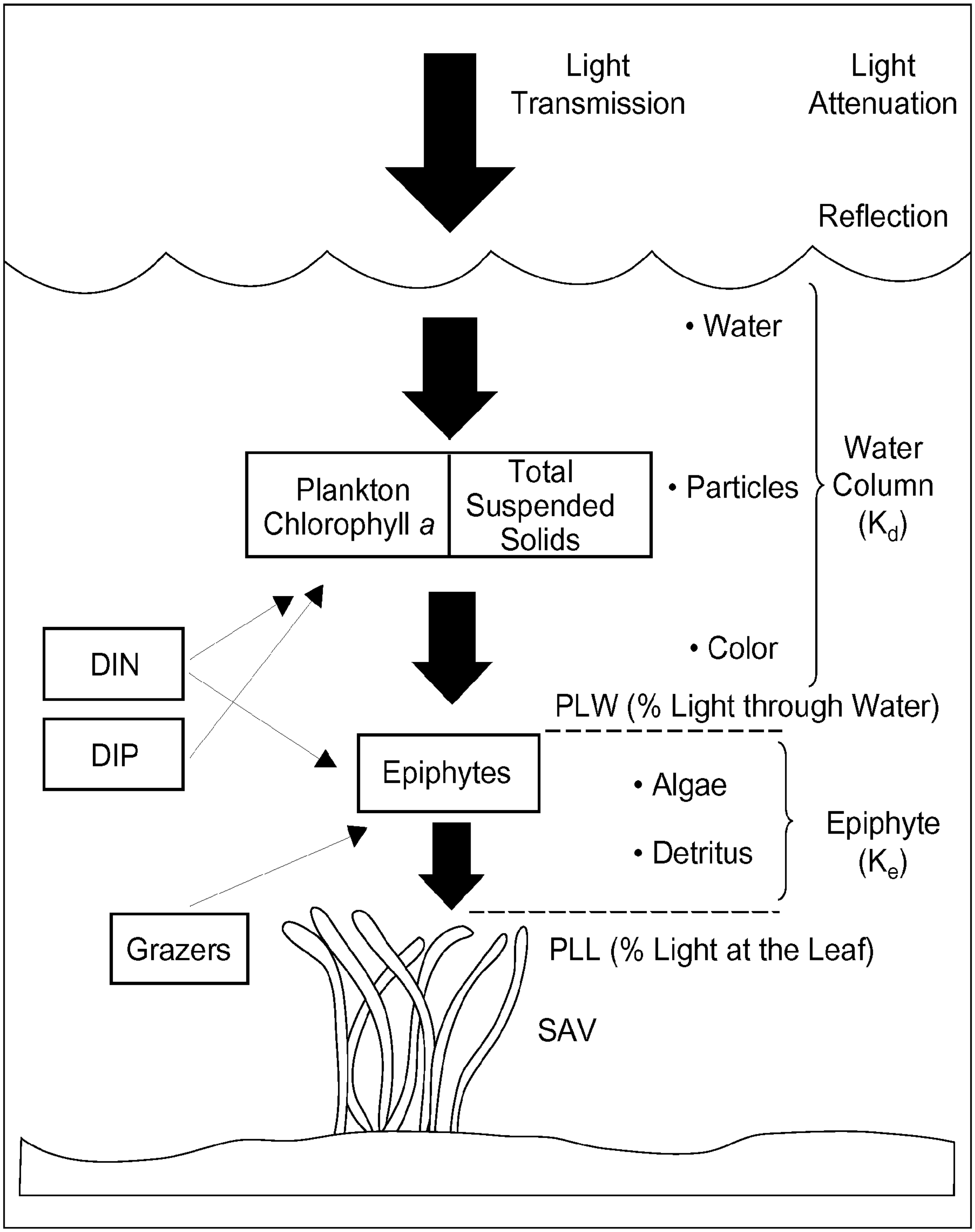

FIGURE II-1. Conceptual Model of Light/Nutrient Effects on SAV Habitat. Availability of light for SAV is influenced by water column and at the leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic nitrogen.

vary considerably from approximately 90 cm at the mainstem Bay mouth to 25 cm on the western side of the upper mesohaline region; tidal ranges on the eastern shoals of the Bay tend to be higher by 10 cm to 15 cm than those on the western side, and ranges are generally 40 cm to 50 cm higher in the tidal fresh regions of tributaries than at their mouths (Hicks 1964). SAV is generally excluded from intertidal areas because of physical stress (waves, desiccation and freezing), and the upper depth-limit for SAV distribution, therefore, tends to be lower in areas with higher tidal range. Furthermore, the deeper depth limit tends to be reduced at sites with greater tidal range because of increased light attenuation through the longer average water column (Koch and Beer 1996). Thus, there tends to be an inverse relationship between tidal range and the range of SAV depth distribution.

In general, there is a strong positive relationship between water clarity and the maximum water-column depth to which plants grow for virtually all SAV species in both freshwater and marine environments (e.g., Dennison *et al.* 1993). Numerous statistical models have been reported describing relationships between K_d (or Secchi depth) and maximum SAV colonization depth. Virtually all of these models are similar in shape and trajectory, and two representative examples are given for freshwater plants (Chambers and Kalff 1985) and seagrasses (Duarte 1991) (Figure II-2, upper panel). There is a suggestion here that freshwater plants tend to survive better than seagrasses in relatively turbid waters (K_d^{-1} < 2 meters), whereas seagrasses grow deeper in clear waters (K_d^{-1} > 3 meters). Realistically, however, the two relationships are quite similar, and the percent of surface light reaching the sediments at the maximum SAV colonization depth (Z_{max}) can be calculated (= exp (- K_d Z_{max})) to range from approximately 10 percent to 30 percent for both habitats. Assuming that light limits the water depth penetration for SAV in most instances, this calculation represents an estimate of the minimum light (as a percent of surface light) required for SAV survival. Results from various shading experiments with different SAV species (primarily with seagrasses) suggest a similar range of minimum light values (10 percent to 35 percent of surface irradiance) at which plants can survive (see Chapter III). These estimates of SAV light requirements, however, don't consider the shading effects of epiphytes addressed in detail in Chapter V.

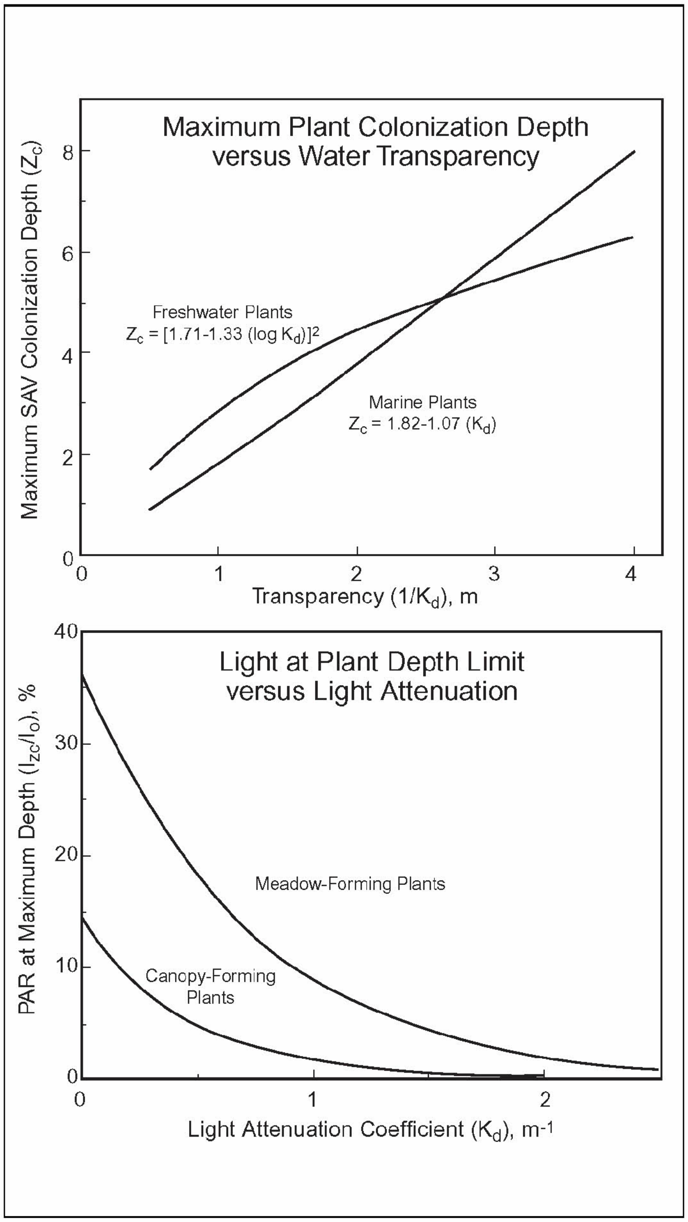

FIGURE II-2. Maximum Plant Colonization Depth. Illustrations of the relationships between water transparency and light attenuation, and maximum depth of SAV growth from fresh water versus marine plants (upper panel) and meadow-forming versus canopy-forming plants (lower panel), respectively.

Whereas seagrasses tend to be meadow-forming species with blade-shaped leaves that grow from their base, most freshwater plants are canopy-formers, with leaves growing out from the tips of stems. Under low-light conditions, these canopy-forming species often exhibit rapid vertical growth by stem-elongation and retain only their uppermost leaves near the water surface (e.g., Goldsborough and Kemp 1988). Canopy-formation and stem-elongation are two shade-adaptation mechanisms that allow these species, which dominate the tidal fresh and oligohaline regions of the Bay, to survive considerably better than meadow-forming seagrasses in turbid shallow environments (Middleboe and Markager 1997) (Figure II-2 lower panel).

This report defines SAV habitat requirements in terms of light availability to support plant photosynthesis, growth and survival. Other physical, geological and chemical factors may, however, preclude SAV from particular sites even when light requirements are met. These effects on SAV are illustrated (Figure II-3) as an overlay on the previous conceptualization (Figure II-1), depicting interactions between water quality variables and SAV light requirements. Some of these effects operate directly on SAV, while others involve inhibition of SAV-light interactions. Waves and tides alter the light climate by changing the water-column height over which light is attenuated and by increasing total suspended solids and associated light attenuation by resuspending bottom sediments. Particle sinking and other sedimentological processes alter texture, grain-size distribution and organic content of bottom sediments, which can affect SAV growth by modifying availability of porewater nutrients (Barko and Smart 1986) and by producing reduced sulfur compounds that are phytotoxic (Carlson *et al.* 1994). In addition, there are diverse pesticides and other anthropogenic contaminants that tend to inhibit SAV growth.

This revised approach for assessing SAV habitat requirements is completely consistent with the Chesapeake Bay Water Quality Model, as the same model structures were used for both calculations. Thus, the Chesapeake Bay Water Quality Model can be used to predict how SAV habitat conditions respond to scenarios for reducing nutrient and sediment loads to the Bay, while the revised SAV habitat assessment approach uses monitoring data to define in quantitative terms recent trends and changes in the suitability the of sites for supporting SAV growth. Although we recognize that factors other than light (including waves, tidal currents, sediments and toxic chemicals) also limit SAV distribution in both pristine and perturbed coastal habitats, we have not yet devised a scheme to explicitly and quantitatively account for them.

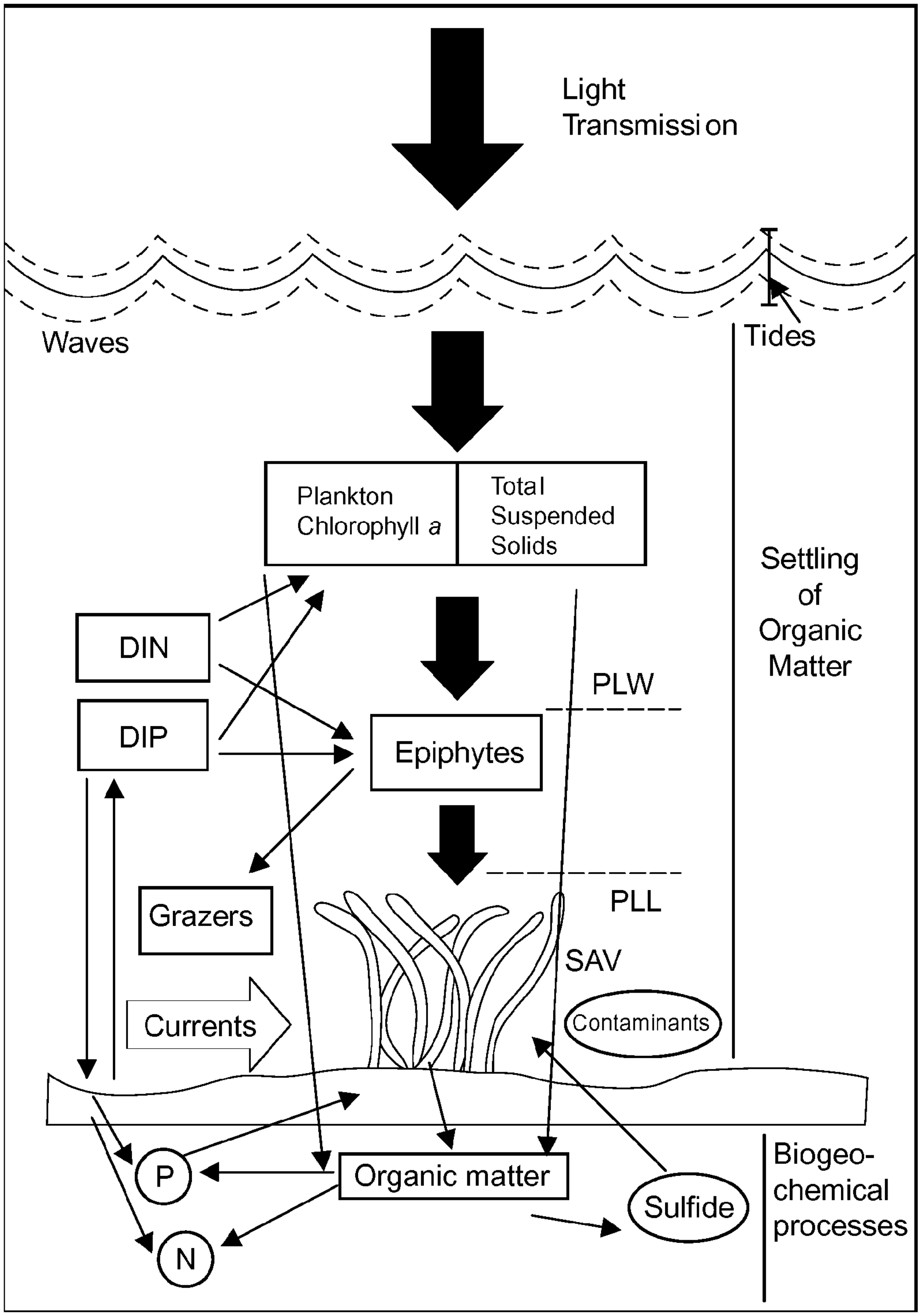

FIGURE II-3. Interaction between Light-Based, Physical, Geological and Chemical SAV Habitat Requirements. Interaction between previously established SAV habitat requirements, such as light attenuation, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), chlorophyll a, total suspended solids (TSS) and other physical/chemical parameters discussed in this chapter (waves, currents, tides, sediment organic matter, biogeochemical processes. P = phosphorus; N = nitrogen; PLW = percent light through water; PLL = percent light at the leaf.

CHAPTER III

Light Requirements for SAV Survival and Growth

This chapter addresses the identification of light requirements for SAV survival and growth as determined by an extensive search of the pertinent literature and examination of experimental results from research and monitoring conducted in Chesapeake Bay. As part of the revision and update of Batiuk *et al.* (1992), emphasis was placed on refining the light requirements, as it is widely recognized that growth, spatial distribution and survival of SAV is ultimately limited by the availability of light to support photosynthesis (Dennison 1987; Duarte 1991a; Middleboe and Markager 1997). Based on available information from four localities in the Bay, Batiuk *et al.* (1992) set habitat requirements for Chesapeake Bay SAV. Light requirements for the various salinity zones of Chesapeake Bay were expressed as light attenuation coefficients (K_d), based primarily on observed K_d maxima or Secchi depth minima at sites with SAV. These light requirements were intended to promote potential recovery of SAV to a depth of 1 meter; that is, plants would be able to colonize all suitable habitats 1 meter in depth.

This chapter also provides a systematic review of the literature on light requirements for SAV, considering the relative utility of information derived from a range of different approaches. Where possible, the information is interpreted in terms of possible differences in light requirements for species and growth forms occurring in the four major salinity zones of Chesapeake Bay. The chapter is divided into three sections: a discussion and evaluation of the literature; factors affecting determination of light requirements for Chesapeake Bay and research and monitoring results from the Patuxent and Potomac rivers; and the water-column light requirements for Chesapeake Bay SAV.

DISCUSSION OF LITERATURE VALUES

Information found in an extensive literature search and review of the light requirements for SAV falls into four general categories: (1) physiological studies of photosynthesis/irradiance relationships; (2) results of field observations of the maximum depth of SAV colonization and available light at that depth; (3) experiments involving the artificial or natural manipulation of light levels during long- or short-term growth studies; and (4) statistical models intended to generalize light requirements. These four categories are discussed in the order of their perceived utility for the purpose of determining light requirements, with models and shading experiments being the most useful. The literature reviewed in this chapter includes lake and estuary studies throughout the world.

Photosynthesis-Irradiance Measurements

Numerous studies have presented photosynthesis-irradiance (PI) curves for SAV. Photosynthesis-irradiance curves are generated by exposing whole plants, leaves, or leaf or stem sections to varying light intensities and measuring the photosynthesis rate based on generation of oxygen or consumption of carbon dioxide (CO_2). Most PI measurements are made in the laboratory, although some studies use ambient light and environmental conditions with plants suspended in bottles at different water depths. Photosynthesis-irradiance curves generally provide information on: (1) species light compensation point (I_c), where respiration balances photosynthesis; (2) light saturation (I_k), or the minimum irradiance at which photosynthesis rates are at a maximum; (3) maximum photosynthesis rate (P_{max}); and (4) the half-saturation constant K_m, which is the irradiance at which one-half the maximum photosynthesis rate (½ P_{max}) is achieved. Such PI data provide the basis for determining the effects of temperature, CO_2 concentration, pH, light conditions during growth of the plant, tissue age, etc., on photosynthesis and its relationship to irradiance. They may also be useful for comparing species if experiments are conducted under similar conditions and/or if plant material comes from the same environment.

These studies show that variables such as light adaptation, water temperature, species, pH, tissue age, CO_2 concentration and nutritional status can all affect rates of photosynthesis and respiration as well as I_c and I_k, making generalizations difficult. Table A-1 in Appendix A is a compilation of literature values for PI studies of freshwater-oligohaline species, most of which are found in Chesapeake Bay and its tidal tributaries.[1] Table A-2 in Appendix A is a summary of literature values from PI studies of mesohaline-polyhaline species, with *Zostera marina* and *Ruppia maritima* being the two species found in Chesapeake Bay and its tidal tributaries. Table III-1 is a summary of the material contained in Appendix A, tables A-1 and A-2, by species.

Photosynthesis-irradiance measurements show that SAV photosynthesis is almost always saturated (I_k) at irradiances from 45-700 μmol m^{-2} s^{-1}. This represents 2.3 to 35 percent of full sunlight (assuming a full sunlight value of 2000 μmol m^{-2} s^{-1}) and indicates that SAV species are adapted to low light regimes rather than surface irradiance. Light compensation points for net photosynthesis (I_c) are very low, generally below 50 μmol m^{-2} s^{-1} (2.5 percent surface light). Light compensation points for overall growth would be higher than those for net photosynthesis, as they would include respiration by above- and below-ground biomass. The half-saturation irradiance K_m ranges from 20-365 μmol m^2 s^{-1} and lies between I_c and I_k for each species.

In considering the utility of PI curves for determining minimum light requirements for restoration of Chesapeake Bay SAV, the following was observed from reviews of the PI values reported in the literature and summarized in Table III-1 and documented in Appendix A, tables A-1 and A-2.

1. I_k depends on temperature and is, therefore, generally lower when temperature is lower (Harley and Findlay 1994; Fair and Meeke 1983; Madsen and Adams 1989; Orr 1988; Marsh *et al.* 1986; Penhale 1977; McRoy 1974; Evans *et al.* 1986; Wetzel and Penhale 1983).

2. I_c generally underestimates the amount of light necessary for growth or survival because it does not take into account the whole plant, including underground biomass. Photosynthesis-irradiance measurements from leaf incubations of *Z. marina* tend to be lower than those for *in situ* incubations or whole plants. However, comparisons are difficult because of the variety of experimental temperatures used and the possibility that whole plants include epiphytes. Likewise, I_k differs according to the experimental conditions. For example, Drew (1979) found *Z. marina* leaf sections to have an I_k of 208 μmol m^{-2} s^{-1} at 15°C, whereas Zimmerman *et al.* (1991) measured I_k at 35 ±17 μmol m^{-2} s^{-1} at the same temperature. Wetzel and Penhale (1983) found whole plants of *Z. marina* at 17.5°C to have an I_k of 312 μmol $^{-2}$ s^{-1} and at 10°C, an I_k of 231 μmol m^{-2} s^{-1}. Furthermore, I_c and I_k measured in the field may be much higher than I_c and I_k measured in the laboratory (Dunton and Tomasko 1994).

3. I_k and I_c vary with *in situ* light intensity gradients, previous daily light history, plant species and leaf and tissue age (Mazzella and Alberte 1986; Goldsborough and Kemp 1988; Bowes *et al.* 1977a; Titus and Adams 1979; Madsen *et al.* 1991; Goodman *et al.* 1995).

Although there are estimates of I_k or I_c for most Chesapeake Bay species, the estimates are so variable depending on experimental conditions, and so few have actually been done in the Chesapeake Bay region, that most studies are not directly applicable for

[1]Freshwater or tidal fresh refers to aquatic habitats with salinities ranging from zero to <0.5 parts per thousand (ppt); oligohaline, to salinities ranging from 0.5 to 5 ppt; mesohaline, to salinities ranging from >5 to 18 ppt; and polyhaline, to salinities >18 ppt.

TABLE III-1. Summary of photosynthesis-irradiance measurements for freshwater, oligohaline, mesohaline and polyhaline SAV species.

Species	I_k (μmol m^2 $s^{-1)}$)	K_m (μmol m^2 $s^{-1)}$)	I_c (μmol m^2 $s^{-1)}$)	References
FRESHWATER AND OLIGOHALINE SPECIES				
Hydrilla verticillata	150-600	27-105	7-20	Van *et al.* 1976, Steward 1991b, Bowes *et al.* 1977a
Myriophyllum spicatum	200-600	90-365	35-84	Van *et al.* 1976, Harley and Findlay 1994, Titus and Adams 1979, Madsen *et al.* 1991, Lloyd *et al.* 1977
Elodea canadensis	-	22	12	Madsen *et al.* 1991
Vallisneria americana	140-179	22-197	10-30	Harley and Findlay 1994, Titus and Adams 1979, Madsen *et al.* 1991
Ceratophyllum demersum	50-700	23-360	5-35	Van *et al.* 1976, Best 1986, Fair and Meeke 1983
Potamogeton spp	-	20-40	10-25	Madsen *et al.* 1991
Potamogeton crispus	45-450	207-245	22-37 w/epiphytes	Baudo 1981, Sand-Jensen and Revsbech 1987
Potamogeton perfoliatus	387-450	95-292	25-55	Harley and Findlay 1994, Baudo 1981, Goldsborough and Kemp 1988
Potamogeton pectinatus	-	173-312	-	Madsen and Adams 1989
Hippuris vulgaris, E canadensis, P. perfoliatus, P. crispus, P. spp	-	102-114	5-15	Maberly 1983
Najas marina	280	-	5	Agami *et al.* 1980
Potamogeton amphifolius	200	-	-	Lloyd *et al.* 1977

(I_c = compensation point; I_k = irradiance at saturation; K_m = 1/2 saturation constant or 1/2 P_{max})

continued

TABLE III-1. Summary of photosynthesis-irradiance measurements for freshwater, oligohaline, mesohaline and polyhaline SAV species *(continued).*

Species	I_k (μmol m^2 s^{-1})	K_m (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	References
Cabomba caroliniana	700	160	55	Van *et al.* 1976
Myriophyllum brasilience	250-300	-	42-45	Salvucci and Bowes 1982
Myriophyllum salsugineum	42-174	-	1.4-17	Orr 1988
MESOHALINE AND POLYHALINE SPECIES				
Ruppia maritima	45-1200		11-88	Evans *et al.* 1986, Koch and Dawes 1991
Zostera marina	7-700	300	0.9-35	Dennison and Alberte 1982, Dennison and Alberte 1985, Marsh *et al.* 1986, Sand-Jensen 1977, McRoy 1974, Evans *et al.* 1986, Koch and Beer 1996, Zimmerman *et al.* 1991, Drew 1979, Mazzella *et al.* 1980
Thalassia testudinum	-	-	14 (40[1])	Fourqurean and Zieman 1991a
Syringodium filiforme	-	-	14 (35[1])	Fourqurean and Zieman 1991a
Halodule wrightii	101-453	-	22-235	Fourqurean and Zieman 1991a, Dunton and Tomasko 1991, Dunton and Tomasko 1994
Other seagrasses	2.0-3.8 mW	-	0.2-0.5	Drew 1979

1. Corrected for respiration

(I_c = compensation point; I_k = irradiance at saturation; K_m = 1/2 saturation constant or 1/2 P_{max})

setting light requirements for survival and growth of Chesapeake Bay SAV. As suggested by Zimmerman *et al.* (1989), it is questionable to use short-term photosynthesis-light experiments to estimate light-growth relationships and depth penetration, particularly when plants are not pre-acclimated to experimental conditions. In addition to the balance between photosynthesis and respiration, estimates of light requirements must consider other losses of plant organic carbon through herbivory, leaf sloughing and fragmentation as well as reproductive requirements. That being said, consider the two studies done in the Chesapeake Bay region (Wetzel and Penhale 1983; Goldsborough and Kemp 1988). The I_c required for the polyhaline species *Z. marina* was as high as 417 μmol m^2 s^{-1} (or about 30 percent, assuming 2000 μmol m^2 s^{-1} light at the surface). For the oligohaline species, *P. perfoliatus*, I_c of 25-60 μmol m^2 s^{-1} (3 percent) was measured in an incubator.

Field Observations of Maximum Depth and Available Light

There have been numerous studies around the world in which observations of the maximum depth to which a species grows (Z_{max}) have been linked to the available light (I_m) at that depth (tables A-3 and A-4 in Appendix A). Determinations of available light are usually made once at midday on a clear day, generally in midsummer, with the available light expressed as the percent of surface or subsurface illumination. These studies are summarized in Table III-2. Some of these studies discuss the problems inherent in determining the percent of surface light needed to restore SAV under various management scenarios.

Individual maximum depth of colonization studies were not particularly useful for setting up minimum light requirements for Chesapeake Bay environments. Most studies were of freshwater and oligohaline species in freshwater lakes, where water was exceedingly clear and the percent of surface light in the middle of the summer on a good day was not really indicative of the seasonal light environment of the plant. All determinations were of the maximum depth at which the plants were rooted, disregarding whether chance fragments or propagules might have established outlier populations that might not survive a whole growing season (e.g., Moore 1996). Measurement frequency is a major problem that needs to be considered with these studies. However, taken in the aggregate, they serve as a basis for models that predict maximum depths of colonization or minimum light requirements (see "Light Availability Models").

With the exception of Sheldon and Boylen (1977), most references in Table III-2 suggested that at the greatest depth where freshwater and oligohaline species were found growing, light was 10 percent of surface light. Sheldon and Boylen (1977) were working in Lake George where the water clarity was excellent—Secchi depths were 6 to 7 meters. This implies a K_d of about 0.19 and a conversion constant of 1.15 to 1.34. They estimated about 10 percent light at 12 meters, the deepest depth at which the plants were found. Compared to the freshwater and oligohaline species, the mesohaline-polyhaline species *Z. marina* required 4.1 to 35.7 percent light at maximum depth; no field observation studies of *R. maritima* were found reported in the literature.

Light Manipulation Experiments

Light requirements for growth and survival of SAV have been investigated directly using short- to long-term studies under experimentally manipulated light conditions (Table III-3). These studies were done *in situ*, in mesocosms where plants receive a measured percentage of ambient light, or in the laboratory where plants are grown under constant light and temperature regimes. Most field studies were done with polyhaline and mesohaline species. In the case of prolonged field experiments, recovery of the plants was sometimes monitored. Some studies did not involve actual manipulation of light levels; e.g., Dunton (1994) involved natural shading by an algal bloom and continuous monitoring of light in Texas coastal bays, whereas Kimber *et al.* (1995) and Agami *et al.* (1984) suspended plants in buckets at specific depths and observed survival. Some studies were included in Table III-3 to provide examples of the various types of experiments, but were not sufficiently robust to be considered directly relevant to determining light requirements for Chesapeake Bay SAV.

Laboratory and mesocosm experiments under highly controlled light, temperature and flow conditions may substantially underestimate natural light requirements because of the absence of natural light variability, herbivory, fragmentation losses and tidal or riverine currents. For example, laboratory shading experiments

TABLE III-2. Summary of percent light at maximum depth of growth for freshwater, oligohaline, mesohaline and polyhaline SAV species from field observations[1]. "Other" refers to species not found in Chesapeake Bay.

Species	Range of Percent Surface Light at Maximum Depth of SAV Growth	References
Hydrilla verticillata	0.46-5.4	Johnstone and Robinson 1987, Canfield *et al.* 1985, Steward 1991b
Elodea canadensis	0.5-5 (10)	Sheldon and Boylen 1977, Johnstone and Robinson 1987, Pip and Simmons 1986, Hutchinson 1975, Meyer *et al.* 1943
Potamogeton pectinatus	5-14 (52)	Howard-Williams and Liptrot 1980, Sheldon and Boylen 1977, Hutchinson 1975
Potamogeton perfoliatus	<2-4 (20)	Sheldon and Boylen 1977, Pearsall 1920
Potamogeton crispus	(52)	Sheldon and Boylen 1977
Ceratophyllum demersum	0.5-3.4	Pip and Simmons 1986, Canfield *et al.* 1985, Hutchinson 1975
Najas flexilis	0.5-3.1 (17)	Sheldon and Boylen 1977, Pip and Simmons 1986, Hutchinson 1975, Meyer *et al.* 1943
Heteranthera dubia	(38)	Sheldon and Boylen 1977, Meyer *et al.* 1943
Vallisneria americana	<2-9 (20)	Sheldon and Boylen 1977, Hutchinson 1975, Meyer *et al.* 1943, McAllister 1991, Kimber *et al.* 1995
Other tidal fresh/oligohaline SAV	2-62	Canfield *et al.* 1985, Hutchinson 1975
Zostera marina	4.1-35.7	Ostenfield 1908, Moore 1991, Zimmerman *et al.* 1991, Dennison 1987, Koch and Beer 1996
Other mesohaline/polyhaline SAV species	10-37	Fourqurean and Zieman 1991b, Onuf 1991, Kenworthy *et al.* 1991, Kenworthy and Fonseca 1996

[1] Numbers in parentheses are from Sheldon and Boylen (1977); see text for further explanation.

TABLE III-3. Results of SAV light manipulation experiments.

Species	Shading method	Shade levels (percent light)	Location	Duration of experiment	Critical percent light[3]	Comments	References
Vallisneria americana	Shade cloth over pond plantings	25, 9, 5 and 2% of seasonal ambient light	Wisconsin	94 day	5%	Replacement tubers at 9%	Kimber et al. 1995
Elodea canadensis[1]	Laboratory growth experiments	0 to 105 µmol m^{-2} s^{-1}	Denmark	30 day	7%	Light level required for root development	Sand-Jensen and Borum 1991
Hydrilla verticillata[1]	Shading experiment in aquaria	0.2, 1, 5, 10, 22, 45, 65, 100% ambient.	Florida	49 day	5%	Hydrilla from Ches. Bay	Steward 1991b
Potamogeton perfoliatus[1]	Shading experiment in aquaria	PAR set at 11, 32, and 100%	Chesapeake Bay	17 day	>11%		Goldsborough and Kemp 1988
Potamogeton pectinatus	Nets over 10x10 m plots	74, 55 and 27% of ambient surface light	Lake Veluwe, Netherlands	8 months/ 1-2 years	27%	Very few tubers, low biomass after 2 years-could recover	van Dijk 1991
P. pectinatus[1]	Muslin layers over plastic pools	Graph in publication shows transmittance	Back Bay/ Currituck Sound, North Carolina	7 months	>4%		Bourn 1932
Najas marina[2]	Plants suspended in buckets at fixed depth in river	Ambient light/ % light controlled by depth.	Israel	growing season	needed 100 µmol m^{-2} s^{-1} to grow and 250 µmol m^{-2} s^{-1} to reproduce	% light depends on having a seasonal average for ambient	Agami et al. 1984

continued

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TABLE III-3. Results of SAV light manipulation experiments (*continued*).

Species	Shading method	Shade levels (percent light)	Location	Duration of experiment	Critical percent light[3]	Comments	References
Ruppia maritima	Shade cloth/ duration various	100, 60, 41, 28, 19, 15 and 7.5% ambient surface light	Australian estuary	61-267 day	28%	The longer the shading, the more light required to 50% productivity.	Congdon and McComb 1979
Zostera marina	Light reduction screens/ water depth 1 ½ m	37% ambient surface light	California	8 months	37%	Turion density decreased to 5% of control.	Backman and Barilotti 1976
Z. marina	Nylon screens	60, 20, 10 and 1.6% ambient surface light	Long Island Sound, New York	n.d.- until death at 20%	20%		Burkholder and Doheny 1968
Z. marina	Outdoor tanks/light reduction screens	94, 61, 41, 21 and 11% ambient surface light	New Hampshire	4 months	11%	Survival at 11% but shoot density decreasing.	Short *et al.* 1995
Heterozostera tasmanica[2]	Light reduction screens	35, 25, 9 and 2 % ambient surface light	Australia	10 months	9%	Might not survive indefinitely at 25% and 35%.	Bulthuis and Woelkerling 1983b
Posidonia australis[2]	Light reduction screens	up to 10% ambient surface light	Australia	3, 6 and 9 months	10%	No recovery after 17 months in 3 month treatment/9 month treatment caused rhyzomes to die.	Fitzpatrick and Kirkman 1995

continued

TABLE III-3. Results of SAV light manipulation experiments (*continued*).

Species	Shading methods	Shade levels (percent light)	Location	Duration of experiment	Critical percent light[3]	Comments	References
Thalassia testudinum[2]	Light reduction screens	5 and 14% ambient surface light/ control was 45% ambient surface light/ av water depth 1.2 m	Corpus Christi, Texas	16 months (490 day)	14%	99% dead	Lee and Dunton 1997
Halodule wrightii[2]	Natural brown algal blooms and increased turbidity with continual monitoring of PAR	41 (Control plants) and 18% (shaded plants) ambient surface light	Texas coastal bays	11 months to 4 years	18%	Continual year-round PAR--natural shading of experimental population by brown tide.	Dunton and Tomasko 1994
Posidonia sinuosa[2]	Light reduction screens	20, 12 and 1% ambient surface light	Australia	8 months for 20% and 1%/ 10-13 months for 12%	20% 12% (longer duration)	2 years shading at 12% would probably collapse bed Longer shading had most severe effect.	Gordon et al. 1994

[1] Experiments designated are not as robust (see main text for details).
[2] Species not found in Chesapeake Bay.
[3] Plants are highly impacted or die at or below this level.

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with the freshwater species *Hydrilla verticillata* and *Vallisneria americana* (Carter and Rybicki, unpublished data, not included in Table III-3) showed that survival for several months was possible under very low light conditions (12 μmol m^{-2} s^{-1})(< one percent of full sunlight 2000 μmol $^{-2}$ s^{-1}), however, tuber formation was severely affected. In this same experiment, survival and tuber production was good at a light level of only 45 μmol m^{-2} s^{-1} (2.3 percent of full sunlight). However, these experiments involved a simulation of growing season photoperiod, rather than the continuously fluctuating daily light environment of the field. Many laboratory/mesocosm studies are of relatively short duration (e.g., Goldsborough and Kemp 1988; Sand-Jensen and Madsen 1991). Agami *et al.* (1984) did not measure or estimate percent light, but merely suggested minimum light for survival or reproduction.

Long periods of dense shading were sufficient to reduce standing crop and below-ground biomass of all species to almost zero. For the mesohaline to polyhaline species, including *R. maritima*, without regard to experimental conditions, the critical percent light ranged from 9 percent to 37 percent, or a mean of 17.9 percent ±2.97 standard error (SE). For *Z. marina* and *R. maritima* (Chesapeake Bay species), the mean was 24 percent ±5.55 SE. In the case of the freshwater-oligohaline species, *V. americana* was able to produce replacement tubers at 9 percent light (94-day growing season) while *Potamogeton pectinatus* was severely impacted when exposed to only 27 percent light (Kimber *et al.* 1995). Pond experiments with *V. americana* by Kimber *et al.* (1995) showed that plants held under 9 percent shading for 94 days under ambient light conditions produced replacement-weight tubers (tubers sufficient to replace the population the following year), however, if the growing season was increased to 109 days, plants produced replacement weight tubers at 5 percent light.

Unfortunately, shading experiments do not provide precise numbers useful for developing light requirements for Chesapeake Bay SAV. If plants die at 10 percent surface light and survive at 20 percent surface light, the actual threshold lies between 10 and 20 percent. Means of light manipulation experiments done under markedly different experimental conditions are not sufficiently accurate to provide guidance for setting light requirements. Reasons for lack of precision include the difficulty in setting up replicates of more than a few light levels and the long duration of the experiments themselves. Because of tidal range, fouling and weather, shading experiments are difficult to do in the field. Some investigators (e.g., van Dijk 1991; Backman and Barilotti 1976; Fitzpatrick and Kirkman 1995) suggest that recovery is possible if light levels increase to those actually supporting a thriving population. This could, of course, be the result of natural revegetation. Backman and Barilotti (1976) mention that revegetation after eight months' shading was primarily due to runners from plants outside the shaded area. Additionally, when shading experiments are conducted, the effect of shading is greatest toward the center of the shaded area where samples are taken, so removal of the shading material can result in vegetative recovery proceeding from the edges toward the center.

Light Availability Models

In recent years there have been attempts to develop statistical regression models to quantify the relationship of light availability to depth of SAV growth based on maximum depth of colonization and water-column light attenuation (Canfield *et al.* 1985; Chambers and Kalff 1985; Vant *et al.* 1986; Duarte 1991a; Middleboe and Markager 1997). Models have also been developed to relate light availability to productivity, primarily in polyhaline species (Zimmerman *et al.* 1994), and to show the relationships of various factors affecting SAV survival (Wetzel and Neckles 1986). Many of the published light requirement models are summarized in Table III-4. Since the models relating depth of colonization and water clarity tend to use large data sets from different habitats, they are considered more robust than models based on single studies or sites. However, some of these models still depend on one-time observations of maximum depth and/or light availability from the literature, similar to observations found in tables A-3 and A-4 in Appendix A (e.g., Canfield *et al.* 1985).

Models for freshwater species are mostly the result of lake studies–light is less variable in lakes than in the estuarine environment where tides, wind resuspension of sediment, algal blooms and river discharge combine to add further complexity. Furthermore, water depth at which the plants are growing and, hence, available light conditions are more stable in a lake than the tidal environment, where available light varies as a function of tidal stage (Carter and Rybicki 1990; Koch and Beer

TABLE III-4. Models relating maximum depth of colonization (Z_{max}) to Secchi depth (SD) or light attenuation coefficient (K_d) and percent of surface irradiance.

Model	Statistics/comments	% of surface light	Methods	Reference
Log (Z_{max}) = 0.61 log (SD) + 0.26 (lake angiosperms- Finland, Wisconsin, Florida) Finland: log Z_{max} = 0.51 log (SD) + 0.18 (n = 27) Wisconsin: log (Z_{max}) = 0.79 log (SD) + 0.25 (n = 55) Florida: log (Z_{max}) = 0.42 log (SD) + 0.41 (n = 26)	r^2 = 0.70 (p<0.01) Overestimates Z_{max} when Secchi depth values are low.	Florida: mean was 3.3± 2.59% (n = 26) Mean irradiance at Z_{max} = about 15μmol m^{-2} s^{-1}	Used Secchi depth Florida: measured K_d concurrently with Secchi depth (10 lakes) Transformed all FL SD to K_d (equation not given) in order to estimate % light.	Canfield *et al.* 1985
$Z_{max}^{0.5}$ = 1.33 log (SD) + 1.4 (Lake angiosperms--Quebec and worldwide) $Z_{max}^{0.5}$ = 1.14 log (SD) + 1.32 (n = 8) Quebec Lakes	r^2 =0.58 (p<0.0001) r^2 =0.50 (p<0.05)	21.4±2.4 over the growing season worldwide 18.16±10.10 over the growing season in Ontario (n=8)	Used mean summer SD. Converted K_d to SD using SD=1.46/K_d . When % transmission data supplied, assumed SD=10%. Total growing season PAR--10% was used to calculate Iz; % light at Z_{max}=I_z/(PAR above the water surface) x 100	Chambers and Kalff 1985
$Z_{max}^{0.5}$ = 1.51 + 0.53 ln SD (n = 160) (Lake angiosperms) (lakes from US, Europe, Asia, New Zealand, Australia)	r^2 = 0.51, (p < 0.0001) Includes tropical and subtropical lakes/latitude has an effect.	Irradiance at Z_{max} is <30% for 78% of the observations.	Measured Secchi depth. Converted K_d to Secchi depth. Secchi depth = 1.47/ K_d (conversions).	Duarte and Kalff 1987

(I_c = compensation point; SI = surface irradiance; PAR = photosynthetically active radiation; p = probability)

continued

TABLE III-4. Models relating maximum depth of colonization (Z_{max}) to Secchi depth (SD) or light attenuation coefficient (K_d) and percent of surface irradiance (*continued*).

Model	Statistics/comments	% of surface light	Methods	Reference
$Z_{max} = 4.34/K_d$ (Lake angiosperms–New Zealand) $K_d = 1.96/SD$ (equation derived from information in text), so $Z_{max} = 2.214$ Secchi depth.	$r^2 = 0.93$ Values of Z_{max} calculated using equations of Canfield *et al.* 1985 and Chambers and Kalff 1985 were far smaller than those found in this study (effect of latitude?).	1.3% Annual mean irradiance at Z_{max}=1-17 μmol m^{-2} s^{-1} (generally equivalent to freshwater I_c).	Measured annual mean K_d and Secchi depth	Vant *et al.* 1986
Caulescent angiosperms Linear relationships: $Z_{max} = 0.37 + 0.95$ SD Nonlinear relationships: $Z_{max} = -0.32 + 2.09$ SD/ sqrt(1 + ((2.09/6.6)*(SD))^2) ln(%SI) = 2.7 + -2.2 K_d (Lake angiosperms—Denmark and international)	Linear model: r^2 =0.58 For nonlinear model: r^2 = 0.55 for %SI = f(K_d), $r^2 = 0.61$ ($p<0.001$) Ranges given for Secchi depth and Z_{max}	5%	Used K_d or Secchi depth Transformed Secchi depth to K_d using K_d = 2.02/Secchi depth to compare results with other publications—result was a much higher % SI at Z_{max} 2.02 came from average of all K_d Z_{max} values where both were given (range 1.06-2.65).	Middleboe and Markager 1997
$Z_{max} = 1.9 + 0.63$ Secchi depth, where Z_{max} = average depth of maximum colonization (Lake angiosperms).	$r^2 = 0.76$, ($p<0.0001$)	no data	Measured Secchi depth. Calculated percent light from SI = $100e^{-kz}$ where K_d is estimated from K_d = 1.47/Secchi depth.	Duarte and Kalff 1990

(I_c = compensation point; SI = surface irradiance; PAR = photosynthetically active radiation; p = probability)

continued

TABLE III-4. Models relating maximum depth of colonization (Z_{max}) to Secchi depth (SD) or light attenuation coefficient (K_d) and percent of surface irradiance (*continued*).

Model	Statistics/comments	% of surface light	Methods	Reference
$Z_{max} = 0.789\ (SD) + 0.581$ (*Thalassia testudinum*)	$r^2 = 0.67$, ($p < 0.01$)	no data	Measured Secchi depth.	Vincente and Rivera 1982
$\text{Log}\ (Z_{max}) = 0.26 - 1.07 \log K_d$ (n = 72) or $Z_{max} = 1.86/K_d$ (seagrasses) *Thalassia testudinum*: $\text{Log}\ Z_{max} = 0.27 - 0.93 \log K_d$ *Z. marina*: $\text{Log}\ Z_{max} = 0.27 - 0.84 \log K_d$	$r^2 = 0.77$, ($p < 0.001$) $r^2 = 0.73$ ($p<0.001$) $r^2 = 0.40$ ($p<0.001$)	10.8%	Used K_d. Converted Secchi to K_d using $K_d = 1.7/SD$.	Duarte 1991a
$Z_{max} = 0.425\ (SD) + 1.259$ (*Z. marina*)	$r^2 = 0.413$ ($p<0.05$)	18% (assuming that 10% of surface light reaches Secchi depth).	Measured Secchi depth monthly.	Olesen 1996
$Z_{max} = 1.62/K_d$ (*Z. marina*) $Z_{max} = 0.95\ SD$		19.8% (calculated from equation) 10% (estimated from relationship with SD).	Measured K_d/calculated SD using $K_d = 1.7/SD$.	Dennison 1987
$\text{Log}\ Z_{max} = 0.55 \log (SD) + 0.32$ (Freshwater angiosperms—Sweden)	$r^2 = 0.542$	no data	Measured Secchi depth; used Chambers and Kalff (1985) data combined with his.	Blindow 1992a

(I_c = compensation point; SI = surface irradiance; PAR = photosynthetically active radiation; p = probability)

1996). A further concern in applying models developed for lake SAV communities to estuaries is that the Secchi depth values in lakes tend to be much larger than those for Chesapeake Bay. Data on depth and colonization are quite sparse for the conditions of interest for Chesapeake Bay (water depths 3 meters, K_d 1.5 m^{-1}). The resulting models were constructed to fit data that were generally different in range from those data for which inferences about light requirements for Chesapeake Bay SAV need to be drawn.

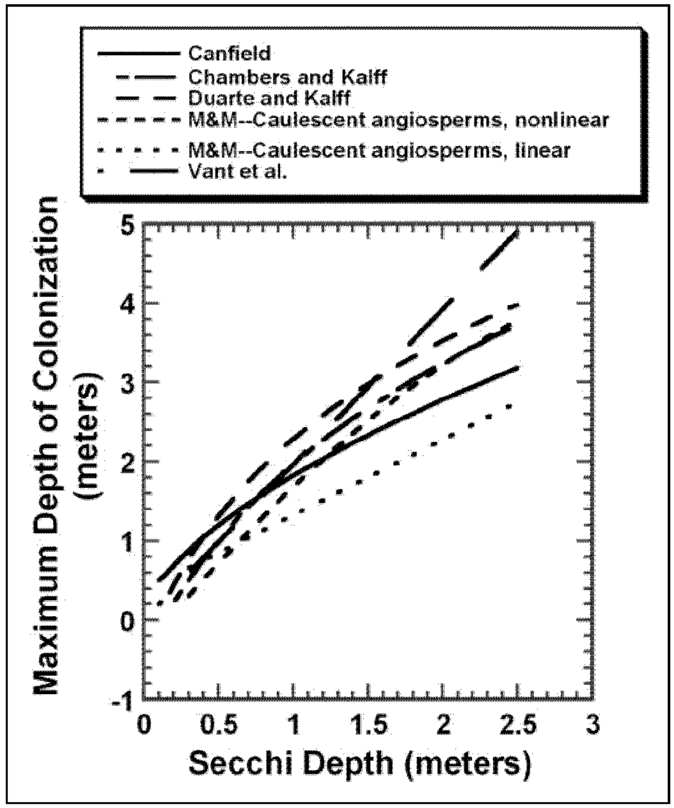

FIGURE III-1. Modeled Relationships of Maximum Depth of Colonization to Secchi Depth for Freshwater Lake SAV Species. Relationship of maximum depth of colonization (Z_{max}) to Secchi depth for freshwater SAV species as modeled by Canfield *et al.* (1985), Chambers and Kalff (1985), Duarte and Kalff (1987), Middleboe and Markager (1997) and Vant *et al.* (1986).

Freshwater and Oligohaline SAV

A series of papers modeled the relationship between light and maximum depth (Z_{max}) of freshwater species, as shown in Figure III-1. Canfield *et al.* (1985) developed a best-fit model for predicting Z_{max} from Secchi depth, based on data from lakes in Finland, Florida and Wisconsin. In the case of the Florida lakes, Secchi depth was determined once during the peak of SAV abundance. Chambers and Kalff (1985) developed regression models to predict Z_{max} using original data on maximum colonization depths and Secchi depth from lakes in southern Quebec and literature values from throughout the world (only the global model is shown in Figure III-1). Duarte and Kalff (1987) examined the effect of latitude on Z_{max} and maximum biomass of SAV in lakes using a data set that included subtropical and tropical lakes, Secchi depth and light attenuation coefficient (K_d) converted to Secchi depth.

Unlike the three studies cited above, which were related to Secchi depth, Vant *et al.* (1986) developed a relationship between monthly measurements of K_d and maximum depth of colonization in nine New Zealand lakes. K_d was converted to Secchi depth using an equation derived from data given in their text (Table 1–Secchi depth = 1.96/ K_d) to give the line shown in Figure III-1. They calculated the mean annual irradiance at Z_{max} (where K_d was available) and found it to be in the range of 1-17 μmol m^{-2} s^{-1}, comparable to light compensation points determined for freshwater SAV species by laboratory studies. They compared their data with other studies that used Secchi depth (Canfield *et al.* 1985; Chambers and Kalff 1985), and found that Z_{max}, as calculated using these equations in the references, was invariably smaller than that observed in New Zealand lakes, and irradiance, as a percent of the subsurface value, was much higher. They suggest this might be an effect of latitude. Note that the major differences in Z_{max} from these studies appear at Secchi depths > 2 meters (Figure III-1).

Middleboe and Markager (1997), working with data from freshwater lakes in the United States, Denmark and other countries, worked out both linear and nonlinear models for estimating Z_{max} from Secchi depth for caulescent angiosperms, tall macrophytes with a distinct stem and long internodes, similar to most of the freshwater and oligohaline species in Chesapeake Bay (Figure III-1). They also modeled rosette-type angiosperms, plants with short, stiff leaves from a basal stem (the isoetids and other species), most of which grow in mats in shallow water and become emergent during the growing season (Likens 1985), but these plants are generally not found in Chesapeake Bay. It appears that Middleboe and Markager (1997) used data on *V. americana* from Lake George

(Sheldon and Boylen 1977) for their analysis, although this species is quite different from the other species in this group. Middleboe and Markager (1997) plotted percent surface irradiance at Z_{max} for those data for which they had K_d (Figure III-2). In order to compare their studies with others, they also calculated percent light at Z_{max} from Secchi depth by converting Secchi depth to K_d using a conversion factor of 2.02 (not shown in Figure III-2). These calculations yielded much higher average percent light values at Z_{max} than those based on K_d values. They pointed out that these considerations demonstrate that it is difficult to draw conclusions about light conditions in the water column only from measurements of Secchi depth. Their percent light values would have been even higher if they had used the Chesapeake Bay Secchi depth to K_d conversion factor of 1.45. They suggested that a nonlinear relationship between Secchi depth and Z_{max} was more appropriate than a linear relationship, even though the r^2 values were comparable, indicating the models explained about the same amount of variance (~55 percent).

Figure III-1 shows a good correspondence among models. For lake species in general, a depth of 1 meter would be colonized when Secchi depth = 0.4 to 0.7 meters. The 0.4- to 0.7-meter range is comparable with the light constraints mentioned by Carter and Rybicki

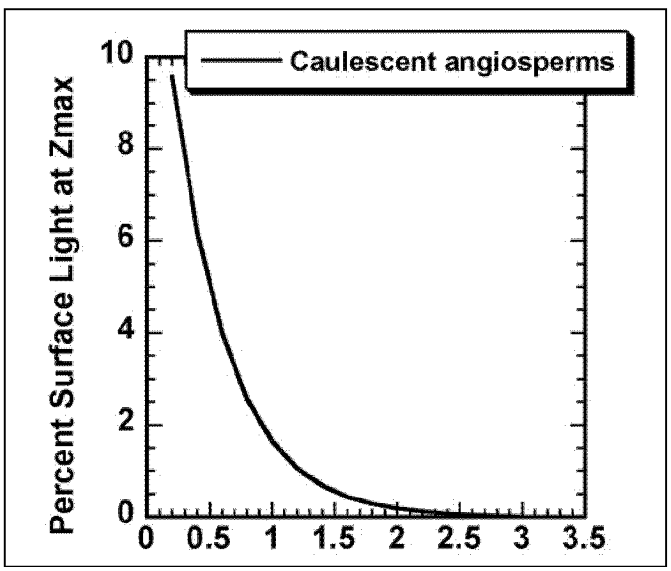

FIGURE III-2. Percent Surface Light at Z_{max}/K_d Relationship for Freshwater Lake SAV Species. Relationship of percent surface light at maximum depth of colonization (Z_{max}) to light attenuation coefficient (K_d) for freshwater lake SAV species (Middleboe and Markager 1997).

in Batiuk *et al.* (1992). Although not considering a target depth of 1 meter, they suggested that when median seasonal Secchi depths were 0.7 meters, SAV beds would increase in size, whereas at Secchi depths 0.5 meters, revegetation would not occur. Between 0.5 and 0.7 meters, other factors, such as epiphyte loading, available sunshine, size and number of tubers set in the previous year, etc., play a role in determining survival.

Batiuk *et al.* (1992) made a distinction between meadow-forming and canopy-forming species in developing light requirements; *V. americana* and *Z. marina* were singled out as meadow-forming species. The distinction between meadow-forming and canopy-forming species, however, blurs at low tide, when all species, including *V. americana* and *Z. marina*, can form a canopy, and at high tide in the tidal rivers, when even *H. verticillata* and *M. spicatum* are well below the water surface. *V. americana*'s light requirements do not appear to be very different from those of the canopy-forming species. In fact, *V. americana* populations in the tidal Potomac River appear to be more tolerant of poor light conditions and persist after canopy formers, such as *H. verticillata,* disappear (Carter *et al.* 1994).

Mesohaline and Polyhaline SAV

Models also have been prepared for several mesohaline to polyhaline SAV species (seagrasses), mostly using Secchi depth to measure light (Figure III-3). All four of these models converge where Secchi depth equals two meters and diverge at Secchi depths above and below this value. Vincente and Rivera (1982) found a significant positive correlation between mean Secchi depth and lower depth limits of *Thalasia testudinum* in Puerto Rico. Duarte (1991a), working with worldwide data, used K_d measurements from the literature or converted Secchi depth to K_d. Duarte then developed a relationship between K_d and Z_{max} for seagrasses, reporting that SAV extends to depths receiving, on average, 11 percent of surface light. Oleson (1996) also developed a relationship between Secchi depth and Z_{max} for *Z. marina* in Denmark. Dennison (1987) found a relationship between K_d and Z_{max} and then developed a relationship between Z_{max} and Secchi depth by using the Poole and Atkins relationship, K_d = 1.7/Secchi depth. Dennison reported that the maximum depth limit for *Z. marina* is approximately equivalent to the Secchi depth, or about 10 percent

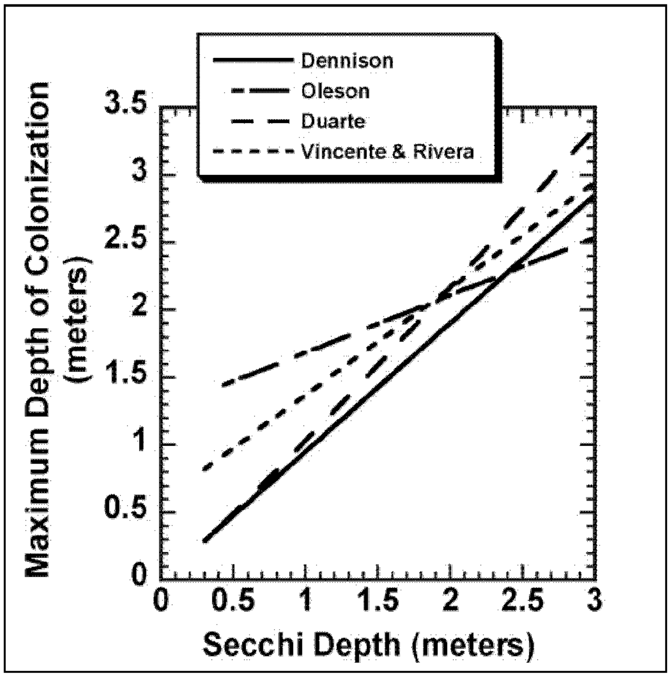

FIGURE III-3. Relationship of Maximum Depth of Colonization/Secchi Depth for Polyhaline SAV Species. Relationship of maximum depth of colonization (Z_{max}) to Secchi depth for polyhaline SAV species as modeled by Dennison (1987), Oleson (1996), Duarte (1991a) and Vincente and Rivera (1982).

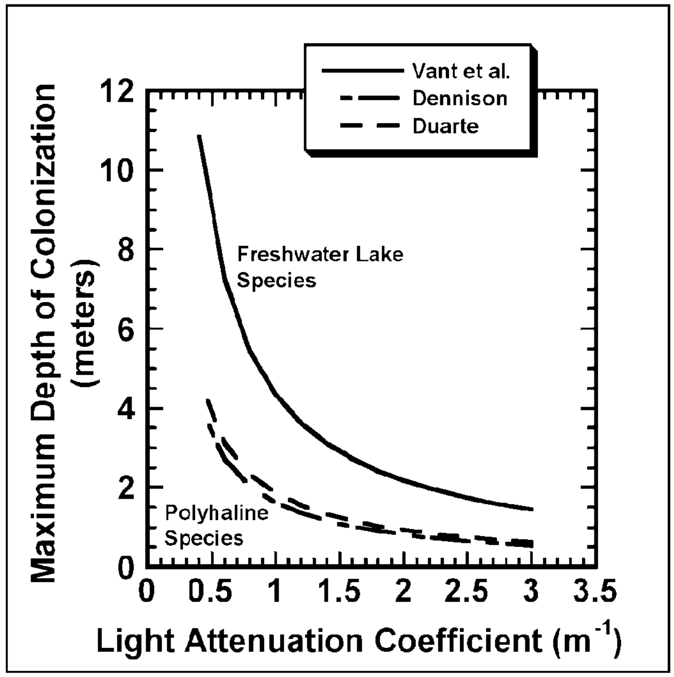

FIGURE III-4. Comparison of Polyhaline and Freshwater Lake SAV Species' Maximum Depth of Colonization/K_d Relationships. Comparison of the relationship between maximum depth of colonization (Z_{max}) and light attenuation coefficient (K_d) for polyhaline and freshwater lake species as modeled by Vant *et al.* (1986), Dennison (1987) and Duarte (1991a).

surface light, but calculations using his equations give 19.8 percent at Z_{max}.

Comparison of Freshwater/Oligohaline Species with Mesohaline/Polyhaline Species

Based on these reported models, it is possible to conclude that there is a significant difference in minimum light requirements for freshwater-oligohaline SAV species and meadow-forming mesohaline-polyhaline SAV species. In order to compare the models for these two sets of species, it is informative to look at models based on Secchi depth and K_d, separately. Only Dennison (1987) and Vant *et al.* (1986) developed a relationship between K_d and Z_{max} using original, unconverted K_d data (Figure III-4). The relationship developed by Duarte (1991a) using a conversion is also plotted in Figure III-4. For any specific light attenuation coefficient, the maximum depth of colonization is much greater for freshwater and oligohaline species, suggesting that a higher percent of surface light is necessary for mesohaline and polyhaline species survival and growth.

Figure III-5 compares the models based on Secchi depth for freshwater/oligohaline species by Vant *et al.* (1986), Duarte and Kalff (1987), and Middleboe and Markager (1997) with those for mesohaline/polyhaline species by Oleson (1996) and Vincente and Rivera (1982). Both Middleboe and Markager's (1997) linear and nonlinear equations are shown, although the nonlinear equation is preferred. Except for the linear equation of Middleboe and Markager (1997), as Secchi depth increases, the colonization depths for mesohaline/polyhaline species and meadow-forming angiosperms diverge further from those for the freshwater/oligohaline species—it appears that the latter grow to greater depths, given the same amount of light. Estimates of percent light available at Z_{max} for freshwater and oligohaline species from the models range from 1.3 percent of surface light to <30 percent of surface light (Table III-4). The estimates of percent light at Z_{max} for mesohaline and polyhaline species range from 10.4 percent to 18.8 percent of surface light.

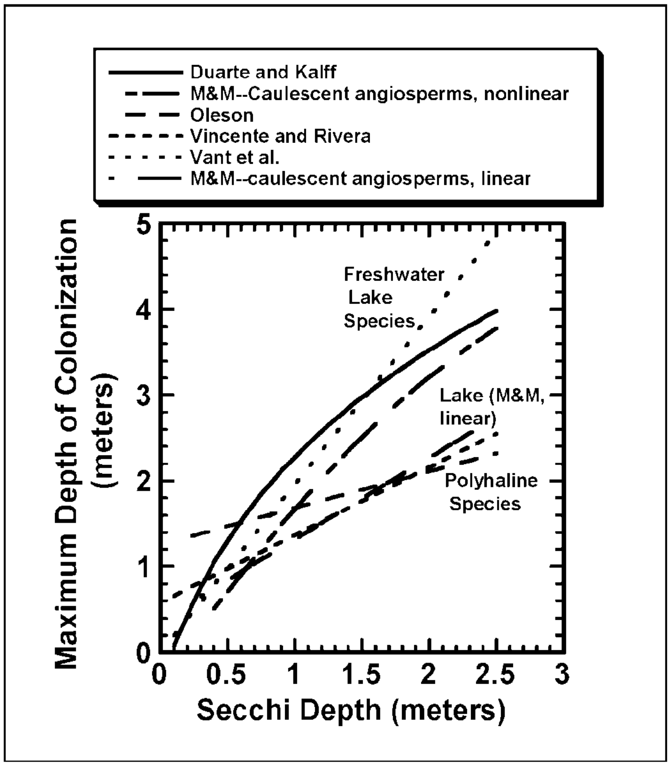

FIGURE III-5. Comparison of Polyhaline and Freshwater Lake SAV Species' Maximum Depth of Colonization/Secchi Depth Relationships. Comparison of the relationship between maximum depth of colonization (Z_{max}) and Secchi depth for polyhaline and freshwater lake SAV species as modeled by Duarte and Kalff (1987), Middleboe and Markager (1997), Oleson (1996), Vincente and Rivera (1982) and Vant *et al.* (1986).

Examination of the four types of evidence for SAV light requirements discussed above—photosynthesis irradiance curves, field observations, light manipulation and models—leads to the conclusion that the models represent the best source of comparative information for developing light requirements for Chesapeake Bay. The shading experiments, although they do not help to refine the light requirements, offer insight into the complexity of plant success under reduced light conditions. The published literature does not provide the specific numbers for Chesapeake Bay SAV light requirements, but can be used to guide decisions and suggest limiting factors. In the section below, we briefly present some of the factors that must be considered in determining light requirements for Chesapeake Bay, along with the results of recent analyses conducted in the Potomac and Patuxent rivers, which support the light requirements recommended later in this report.

DETERMINATION OF MINIMUM LIGHT REQUIREMENTS FOR CHESAPEAKE BAY

Factors To Be Considered in Determining Minimum Light Requirements

Lack of Literature Concerning Many Species in Estuarine Environments

Although there is an abundance of literature about the relationships between light availability and SAV distribution in freshwater lakes and polyhaline environments, there is relatively little such information on SAV in tidal fresh, oligohaline and mesohaline estuarine environments. These environments are often characterized by high turbidity, tidal fluctuations, variable salinity and high-energy events (e.g., wind and waves). If information from freshwater lake SAV studies is used to guide the selection of light requirements for the bay, it is especially important that Chesapeake Bay research and monitoring results be used to adapt and fine-tune these requirements.

Uncertainties in the Relationship between Secchi Depth and K_d

In tidal waters there is high variability in K_d because estuarine water columns are highly variable in time and space. Zimmerman *et al.* (1994) have shown that the daily light integral is not well approximated by sinusoidal theory. There is considerable uncertainty regarding the conversion of Secchi depth to K_d (e.g., Kirk 1994; Giesen *et al.* 1990). Table III-5 lists some of the conversion factors found in the literature. Some authors have discussed the inconsistencies introduced by conversion (e.g., Vant *et al.* 1986; Middleboe and Markager 1997). Chesapeake Bay Water Quality Monitoring Program Secchi depth measurements are made to the nearest decimeter, thus rendering these measurements insensitive in very turbid waters. Until K_d measurements are routinely collected or the sensitivity of the Secchi measurements is increased beyond the nearest decimeter, it is recommended that use of the conversion factor of 1.45, published by Batiuk *et al.* (1992) be continued for consistency.

Uncertainties in Measurement of Percent Light

There is a similar problem encountered in comparing estimates of percent light based on underwater measurements of flux to those based on K_d. The light

TABLE III-5. Conversion of Secchi depth (SD) to K_d, Secchi depth equivalences, and percent light at the 1-meter depth for Secchi depths equal to 0.5, 1.0 or 2.0 meters.

Formula	Percent light at 1 meter			References	Source
	SD = 0.5 m	SD = 1.0 m	SD = 2 m		
$K_d = 1.45/SD$	5.5	23.5	48.4	Batiuk et al. 1992	
$K_d = 1.7/SD$	3.3	18.3	42.7	Poole and Atkins 1929	Geisen 1990, Duarte 1991a
$K_d = 1.44/SD$	5.6	23.7	48.7	Holmes 1970	Geisen 1990
$K_d = 1.25/SD$	8.2	28.7	53.5	Visser 1970	Geisen 1990
$K_d = (2.6/(SD+2.5))-0.0480$	44.1	49.9	58.9	Weinberg 1976	Geisen 1990
$K_d = 1.052 * SD^{-0.536}$	21.8	34.9	48.4	Pellikaan 1976	Geisen 1990
$K_d = 1.47/SD$	5.3	23.0	48.0	Duarte and Kalff 1987	
$K_d = 1.46/SD$	5.4	23.0	48.0	Chambers and Kalff 1985	
$K_d = 2.02/SD$	1.8	13.3	36.4	Middleboe and Markager 1997	
SD = 15% subsurface intensity *Implies $K_d = 1.90/SD$	2.2	15	38.7	Vollenweider 1971	Vincente and Rivera 1982
SD = 18-24% subsurface intensity *Implies $K_d = 1.71/SD$ to $1.43/SD$	3.3 to 5.7	18.1 to 23.9	42.5 to 48.9	Backman and Barilotti 1976	Vincente and Rivera 1982
SD assumed = 10% light level *Implies $K_d = 2.30/SD$	1.0	10.0	31.7	Chambers and Kalff 1985	
SD = 22% surface irradiance *Implies $K_d = 1.51/SD$	4.9	22.1	47.0	Megard and Berman 1989	Dunton 1994

*Note: $K_d = \ln(I_o/I_{SD})/SD$

attenuation coefficient, K_d, gives the relationship between simultaneous measurements of irradiance at depth and irradiance just below the surface of the water. Estimates of percent light based on actual flux at depth Z can be calculated using full sunlight, estimated here as 2000 μmol m^{-2} s^{-1}, or some more medium condition, for example, 1500 μmol m^{-2} s^{-1} or even a less sunny condition, 1000 μmol m^{-2} s^{-1}, but these are not equivalent to percent light based on actual K_d. Tables III-5 and III-6 illustrate how sensitive percent light estimates are to assumptions made for calculations and explain why there has been no attempt in this chapter to estimate the percent light plants were receiving based on measured fluxes without surface or below-surface reference measurements.

Importance of Short-Term Events

Existence of SAV beds is assumed to depend upon the average light climate over a growing season, but short-term periods of light limitation can also influence plant survival, as has been demonstrated for *Z. marina* populations in tidal tributaries of lower Chesapeake Bay (Moore *et al.* 1997). Canopy formers are most vulnerable to high turbidity during the early growing season, when plants are growing rapidly toward the surface. If overwintering plant propagules are small or few in number or if plants reproduce by seeds, the impact of early spring turbidity could be serious. Seasonal or short-term events that significantly reduce light availability may cause annual estimates of light availability to be misleading by overestimating average light availability (Moore *et al.* 1997).

Relative Light Requirements for Canopy-Forming vs. Meadow-Forming Species

It is important to recognize that different SAV species with diverse growth strategies and/or growing in different habitats may have substantially different light requirements. Light requirements in tidal fresh and oligohaline environments may differ from those in mesohaline and polyhaline environments not only because of salinity stress, but also because of differences between canopy formers and meadow formers. All the polyhaline species, including *Z. marina,* are meadow species; most of the tidal fresh to oligohaline species are canopy formers, with the exception of *V. americana.* The biomass of canopy formers is generally concentrated in the top half of the water column, whereas the biomass of meadow formers such as *V. americana* or *Z. marina* is concentrated in the lower two-thirds of the water column (Carter *et al.* 1991; Titus and Adams 1979).

Canopy formation requires rapid growth toward the surface during the early growing season and results in the shading of plants or plant parts below the canopy and the shedding of lower leaves. Epiphytes accumulate on the older parts of the foliage where they are sloughed off with the leaves; continued growth produces "epiphyte-free" apical leaves. In meadow formers, the new leaf tissue is near the base of the plant, whereas older leaf tissue near the surface may be heavily epiphytized; however, the leaf turnover rate is fairly rapid because the life span of leaves is two months (Sand-Jensen and Borum 1983).

TABLE III-6. Percent light calculated from light flux at depth Z based on estimates of ambient surface light.

Light flux at depth Z (μmol m^{-2} s^{-1})	Percent light based on ambient full sunlight (2000 μmol m^{-2} s^{-1})	Percent light based on ambient 1500 μmol m^{-2} s^{-1}	Percent light based on ambient 1000 μmol m^{-2} s^{-1}
10	0.5	0.7	1
50	2.5	3.3	5
100	5	6.7	10
200	10	13.3	20
300	15	20	30

Morphological Adaptions to Low Light

In highly turbid environments the relationship between available light and plant survival tends to break down because of the effectiveness with which certain SAV species can employ morphological adaptations, including leaf and stem etiolation, to cope with low light in very shallow habitats (Middleboe and Markager 1997). In some cases, plant seedlings and vegetative sprouts can reach the water surface quickly by concentrating on vertical growth and cell elongation. Once photosynthetic tissue approaches the water surface there will be sufficient light to maintain positive net growth (e.g., Goldsborough and Kemp 1988).

Beginning Growing Season Carbohydrate Reserves

Rapid elongation toward surface light is helped by the presence of large propagules (e.g., tubers and turions) containing considerable stored carbohydrate reserves (e.g., *V. americana, H. verticillata, P. pectinatus, P. crispus*). However, in years when light availability is poor, fewer and smaller overwintering propagules may be produced or less below-ground biomass built up, thus influencing the following year's growth.

Middleboe and Markager (1997) suggest that the minimum light requirements for SAV depend on the plant-specific carbon value (plant biomass per unit light absorbing surface) for the species/group, indicating that the light requirements of SAV are tightly linked to the plant's ability to harvest light and, hence, to the growth form. The above-ground shoot biomass, along with the specific leaf area for the shoot, determines the area available for light harvesting per unit of plant biomass and thus plant-specific carbon. Plants with a high plant-specific carbon value have a limited capacity to tolerate losses, due to grazing or mechanical damage, at low light. For perennial species, initial growth often is supported by reserves of carbohydrates stored in below-ground structures or shoots, allowing plants to achieve high initial elongation rates despite low irradiance and to form canopies in the upper, well-illuminated part of the water column. Colonization occurs either vegetatively from shallower water or from propagules during periods with clear water and/or high surface irradiance. High spring turbidities also may limit survival of high-salinity species by reducing the carbohydrate reserves necessary for survival during periods of temperature stress in the summer (Burke *et al.* 1996; Moore *et al.* 1997).

Light Attenuation by Epiphytic Material

Photosynthetically active radiation (PAR) attenuation by epiphytic material accumulating on SAV leaves, which is seldom considered in shading experiments or Z_{max} vs. K_d models, will cause the minimum light values cited in these studies to be overestimates of actual plant requirements. Under typical healthy field conditions (early to mid growing season), light attenuation across accumulated epiphytic material causes an additional 15 percent to 25 percent reduction of transmitted light to polyhaline and mesohaline species (e.g., Bulthuis and Woelkerling 1983b; Staver 1984; Twilley *et al.* 1985; Kemp *et al.* 1989; van Dijk 1993; Vermaat and Hootsman 1994). Almost no information is available in the literature on the effects of epiphytic material on light availability for fresh or oligohaline species.

Chesapeake Bay Research and Monitoring Findings

Research and monitoring results from Chesapeake Bay also provide insights into light requirements, especially in tidal fresh and oligohaline waters where there is a paucity of published information. Batiuk *et al.* (1992) established minimum seasonal water-column based light requirements by salinity regime for restoration of SAV to a depth of 1 meter throughout Chesapeake Bay: $K_d = 2.0\ m^{-1}$ in tidal fresh and oligohaline regimes and $K_d = 1.5\ m^{-1}$ in mesohaline and polyhaline segments. Using the relationship

$$\text{percent light} = 100 * \exp(-K_d * Z) \qquad \text{(III-1)}$$

where Z = depth in the water column, and setting Z = 1 meter, the Chesapeake Bay minimum seasonal percent light requirement as published in Batiuk *et al.* (1992) was 13.5 percent in tidal fresh and oligohaline environments and 22.3 percent in mesohaline and polyhaline environments. More specific water-column based seasonal light requirements were suggested by Carter and Rybicki in Batiuk *et al.* (1992) for the tidal Potomac River and Estuary: $K_d = 2.2\ m^{-1}$ in tidal fresh regions and $K_d = 2.7\ m^{-1}$ in oligohaline regions. In the Potomac River and Estuary, the suggested water-column based seasonal light requirements by Carter and Rybicki in Batiuk *et al.* (1992) were 11 percent in the tidal fresh and 7 percent in the oligohaline environments.

Tidal Fresh/Oligohaline Potomac River Findings

Before 1997, the Chesapeake Bay Program subdivided the tidal Potomac River and Estuary into three salinity-based segments—TF2 (tidal fresh), RET2 (oligohaline to mesohaline) and LE2 (mesohaline), for the purpose of analyzing data and comparing tributaries baywide. These segments were later redefined, but SAV coverage for TF2 rather than the newer and less inclusive Chesapeake Bay Program segment POTTF1 was used for this analysis. Biweekly water-quality monitoring data were acquired from the Maryland Department of Natural Resources. Annual SAV coverage in the tidal Potomac River and Estuary mapped by the Virginia Institute of Marine Science was acquired from the Chesapeake Bay Program. SAV coverage estimates for segment TF2 and stations therein for 1983 were made on the basis of extensive field work by Carter and Rybicki during the 1983 growing season. SAV coverage estimates for 1988 for segments TF2 and POTOH were made from 1:12,000-scale color aerial photographs acquired for the Metropolitan Washington Council of Government's Aquatic Plant Management Program.

From 1983 through 1996, SAV coverage in the Potomac River varied greatly in both the TF2 and the POTOH segments, as shown in Figure III-6. Both the change in SAV coverage from the previous year (Figure III-7) and the median percent light calculated from growing season Secchi depth (Figure III-8) varied greatly, but both exhibited a general downward trend during this period.

The change in SAV coverage from the previous year can be plotted against the median percent light at 1 meter during the SAV growing season (April–October), as shown in Figure III-9. Changes in SAV were generally related in a positive, increasing manner to percent light. When median percent light was greater than 13 percent, SAV coverage showed only positive increases over three years. However, positive increases occurred even in years when median percent light at 1 meter was considerably less than 13 percent, indicating that other factors besides light also influence changes in coverage, or that SAV was growing at depths < 1 meter. A median growing season percent light of 13 percent at 1 meter is equivalent to a median Secchi depth of 0.7 m or median K_d=2.07, assuming K_d = 1.45/Secchi depth. Secchi depth is only reported to 0.1 m, so the error in the median measurements is

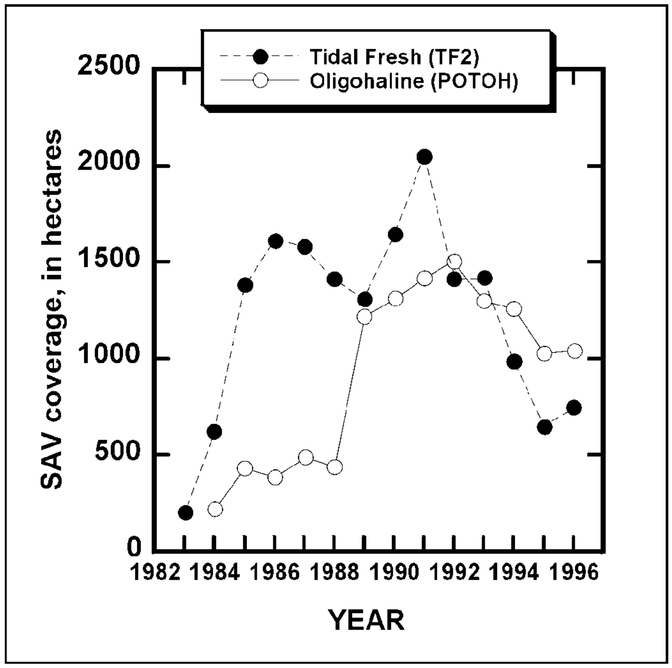

FIGURE III-6. Potomac River Tidal Fresh/Oligohaline SAV Coverage. Seasonal SAV coverage from 1983-1996 for the Potomac River's tidal fresh and oligohaline segments.

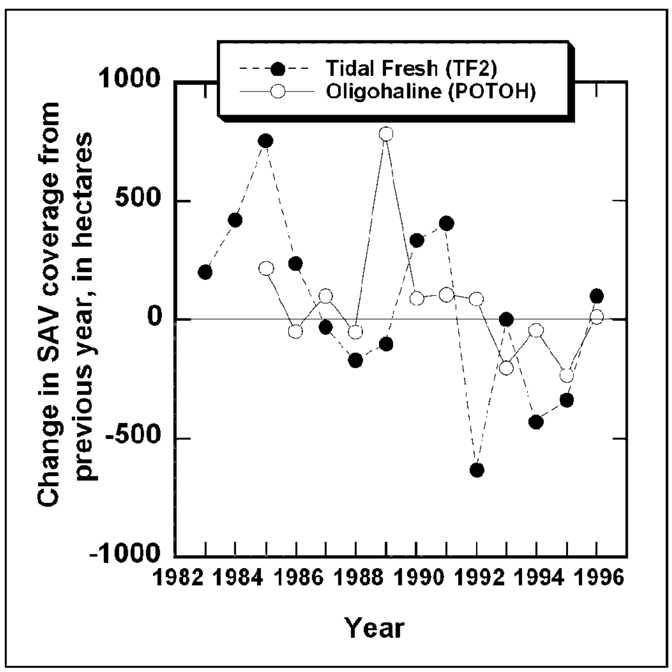

FIGURE III-7. Change in Seasonal SAV Coverage for Potomac River Segments. Changes in seasonal SAV coverage from previous year, in hectares, for the tidal fresh (TF-2) and oligohaline (POTOH) Potomac River segments from 1983-1996.

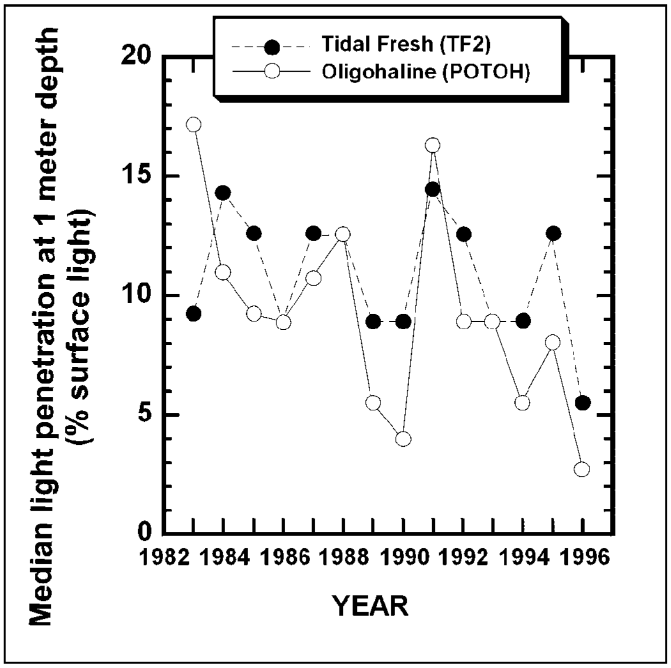

FIGURE III-8. Change in SAV Growing Season Light Penetration for Potomac River Segments. Median percent light at the one-meter depth during the April-October SAV growing season for the tidal fresh (TF2) and oligohaline (POTOH) Potomac River segments from 1983-1996, assuming K_d = 1.45/Secchi depth.

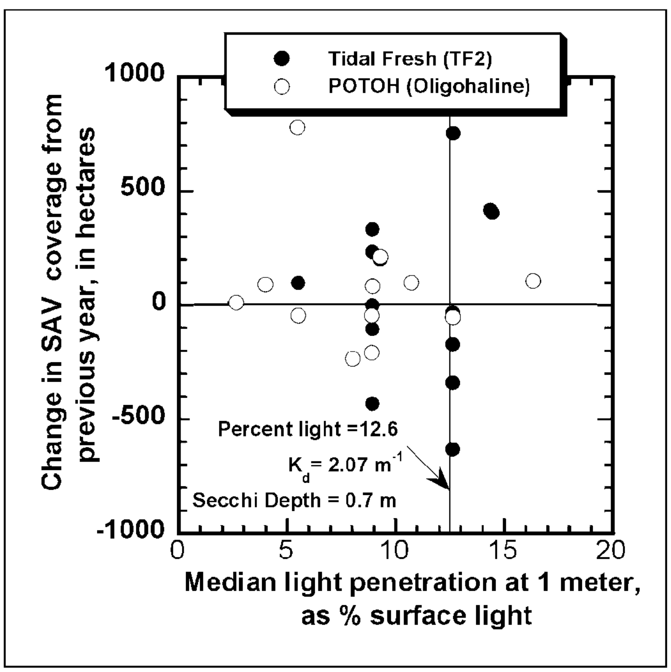

FIGURE III-9. Change in SAV Coverage in Relation to Light Penetration. The change in SAV coverage from the previous year in the tidal fresh (TV2) and oligohaline (POTOH) segments of the Potomac River is shown in relation to the median percent light at the one-meter depth during the April-October SAV growing season.

±0.05 m, median seasonal Secchi depth ranges from 0.65 to 0.75 m and, therefore, K_d ranges from 1.93 to 2.23 m^{-1}. This suggests that for the tidal fresh and oligohaline segments of the Potomac River and Estuary, a corresponding range of percent light of 11 percent to 14.5 percent presents a boundary condition for net increase in growth from year to year. It should also be noted that if other habitat conditions are favorable, SAV may tolerate worse light conditions for a season, but not on a protracted basis.

Tidal Fresh Patuxent River Findings

The tidal Patuxent River is a lower energy environment than the tidal Potomac River in terms of river width and fetch, so that plants may be able to colonize shallower areas than possible in the Potomac River. After having no SAV for many years, the tidal fresh Patuxent River (PAXTF) had notable SAV for the years 1993 through 1998. Corroboration of the SAV light requirements suggested by the Potomac data comes from observations on the Patuxent River.

For the period of 1985 to 1996, light conditions in the tidal fresh Patuxent River (Maryland Department of Natural Resources monitoring station PXT0402) improved. K_d dropped from 6 m^{-1} to about 4 m^{-1} (Mike Naylor, unpublished data) and average Secchi depth increased from 0.25 to 0.4 meters. During the last four years of this period, colonization by SAV also increased, primarily in the shallow areas less than 0.5 meters deep mean lower low water (MLLW). A K_d of four results in 13.5 percent light at a depth of 0.5 meters. A second Patuxent River tidal fresh water quality monitoring station (PXT0456) also showed a significant increase in Secchi depth during the SAV growing season in this same period.

It appears that when the seasonal Secchi depth at PXT0456 was greater than a threshold value of 0.35 meters, the SAV coverage continued to increase, whereas a Secchi depth below 0.35 meters coincided with a decrease in SAV coverage. A Secchi depth threshold of 0.35 meters for plants colonizing a depth of less than 0.5 meters is equivalent to a 0.68-meter Secchi depth threshold for plants colonizing a depth of less than 1 meter (as seen in the Potomac). Thus it appears that similar threshold light conditions are required for successful recolonization in the tidal fresh areas of both the Potomac and Patuxent rivers.

Mesohaline Potomac Findings

In the mesohaline segment of the Potomac River, SAV has continued to increase steadily since 1983, although the coverage remains relatively small compared to pre-1960 conditions. Colonization by SAV has taken place primarily in areas less than 1 meter deep. Midchannel light conditions are better in the mesohaline segment of the river compared to either the tidal fresh or oligohaline segments, with the median seasonal Secchi depth generally never dropping below 1 meter for the period 1983-1996. Secchi depth is only reported to 0.1 meters, so the error in the median measurements is at least ±0.05 meters. If median Secchi depth is 1 meter, then using a conversion factor of 1.45 to calculate K_d, median light conditions are 23.5 percent at 1-meter depth (MLW), ranging from 21.7 percent to 25.1 percent. Thus, it appears that the Chesapeake Bay water-column based light requirements published previously by Batiuk *et al.* (1992) for mesohaline and polyhaline segments are consistent with what has been seen in the mesohaline region of the Potomac River.

WATER-COLUMN LIGHT REQUIREMENTS

Based on an in-depth review of the results of shading experiments and model findings published in the scientific literature, a water-column light target of >20 percent is needed for Chesapeake Bay polyhaline and mesohaline species. Consistent with the value derived from the extensive scientific literature review, the water-column light requirement of 22 percent was determined for mesohaline and polyhaline regions of Chesapeake Bay and its tidal tributaries by applying the 1992 SAV habitat requirement for K_d (=1.5 m^{-1}, Table VII-1) through the equation for determining the percent light through water, PLW (see Chapter V):

$$PLW=100[\exp(-K_d)(Z)] \qquad \text{(Equation II-1).}$$

Considering measurement precision in Secchi depth measurements, this requirement has a margin of uncertainty that can be expressed as 21-24 percent light for the mesohaline and polyhaline segments. This water-column light requirement is confirmed by field observations since 1983 in the mesohaline Potomac River (21.7 percent to 25.1 percent; see "Mesohaline Potomac Findings").

Based on published model findings, confirmed by a review of the results of recent tidal Potomac and Patuxent River research and monitoring studies, a water-column light requirement of 13 percent light is recommended for Chesapeake Bay tidal fresh and oligohaline species. This water-column light requirement calculated using Equation II-1 and the appropriate 1992 SAV habitat requirement for K_d (<2 m^{-1}, Table VII-1). Considering measurement precision in Secchi depth measurements, these water-column based light requirements have a margin of uncertainty that can be expressed as 11 percent to 14.5 percent light for the tidal fresh to oligohaline segments. The literature suggests that field requirements are three to five times greater than minimal light conditions measured in a laboratory, and the only lab experiment for tidal fresh Chesapeake Bay SAV species (Goldsborough and Kemp 1988) yielded a light requirement of 3 percent. We suggest about a fourfold multiplier to 13 percent because this is consistent with what has been seen in the Potomac and Patuxent rivers. This water-column light requirement is also consistent with the 13.5 percent requirement published by Batiuk *et al.* (1992) and Dennison *et al.* (1993).

The large and diverse literature describing responses of different SAV species to variations in light regime under field and laboratory conditions has been summarized in this chapter. The material here points to the need for different water-column light requirements for different salinity zones in Chesapeake Bay, largely because of species differences. Chapter VI also illustrates that tidal range may drastically alter available light and may be a factor in determining the area available for colonization. Targeting a specific percentage of light makes these light requirements more universally usable than does specifying K_d for restoration of vegetation to a particular depth. Until more definitive research is conducted, these requirements should be considered with a margin of uncertainty based primarily on the measurement error built into the Secchi depth measurement.

Chapter V, "Epiphyte Contributions to Light Attenuation at the Leaf," focuses on how changes in water quality alter the light available at SAV leaves, considering not only the water-column attenuation, but also the attenuation of light by epiphytic algae, organic detritus and inorganic particles attached to the leaf. Based on the application of the spreadsheet model of Chapter V for calculating PAR attenuation by epiphytic material accumulating on SAV leaves, the water-column light requirements described here can be translated into minimum light requirements based on both water-column and epiphytic attenuation, as described in Chapter VII.

CHAPTER IV

Factors Contributing to Water-Column Light Attenuation

The penetration of sunlight into coastal waters places severe constraints on the survival and spatial distribution of submerged aquatic vegetation. Currently the best estimate for the minimum amount of light required for survival of SAV is as high as 22 percent of incident sunlight for mesohaline and polyhaline estuarine species (Chapter III).

Light penetration through the water column is controlled by the amount and kinds of materials that are dissolved and suspended in the water. Quantitative understanding of the mechanisms by which the various materials affect the transmission of light through water forms the basis for setting water quality requirements for the restoration and protection of SAV. Light reaching the surface of an SAV leaf is further attenuated by attached epiphytic algae and other mineral and organic detritus adhering to the leaf. Therefore, target concentrations of optically active water quality constituents must be regarded as minimum requirements for SAV survival and growth, which may be modified as needed by conditions that promote growth of epiphytic algae on leaf surfaces (Chapter V).

This chapter documents the development and management application of diagnostic tools for defining the necessary water quality conditions to develop goals and management actions for restoring and protecting SAV. The diagnostic tool pertains only to water quality conditions that influence light attenuation within the water column. The additional light attenuation occurring at the leaf surface due to the accumulation of epiphytes and associated material is addressed in Chapter V. The process of light attenuation underwater is briefly summarized. It will be shown that, in spite of known nonlinearities, a linear expression relating the attenuation coefficient to water quality concentrations is all that is justifiable, because of the variability in the optical properties of the water quality constituents and in the measurements. The diverse origins of suspended particulate matter is one factor that increases the difficulty of modeling light attenuation over such a large geographic extent as Chesapeake Bay. The contribution of phytoplankton to total suspended solids is estimated to better define the relative roles of nutrient reduction and sediment controls increasing light penetration for different locations. The use of a linear model of light attenuation to plot a range of water quality conditions that will result in depth specific attainment of minimum light requirements is then demonstrated.

WATER-COLUMN LIGHT ATTENUATION

Light underwater is diminished by two processes: absorption and scattering (Kirk 1994). Absorption removes light altogether, whereas scattering changes the direction of propagation. Scattering does not directly remove light from the water, but rather increases the probability that it will be absorbed, by increasing the path length or distance that the light must travel.

Absorption and scattering interact in a complex and nonlinear manner to govern the attenuation of light underwater. The equations governing the propagation of light underwater, called the radiative transport equations, have no exact solution; but several computer programs have been written to solve the equations by various numerical methods (Mobley *et al.* 1993). Despite the complexities of the radiative transport equations, field measurements of underwater irradiance nearly always show a negative exponential decay of light with depth. In the absence of strong discontinuities in water quality, such as nepheloid layers, subsurface chlorophyll *a* maxima or humic-stained surface layers, measurements of photosynthetically active radiation (PAR, 400-700 nm) are well described by a single exponential equation of the form

$$I_{Z2} = I_{Z1}\exp[-K_d(Z_2 - Z_1)] \qquad \text{(IV-1)}$$

where I_{Z1} and I_{Z2} are irradiances at depth Z_1 and Z_2 ($Z_2 > Z_1$), and K_d is the diffuse attenuation coefficient for PAR. Several expressions useful for describing the light available to SAV are easily derived from Equation IV-1. For example, if Z_1 represents the surface (depth=0) and Z_2 is the maximum depth of SAV colonization, Z_{max}, then the percentage of surface light penetrating through the water (PLW) to the plants at depth Z_{max} is given by

$$PLW = \exp(-K_d Z_{max})*100 \qquad \text{(IV-2).}$$

We denote the minimum PLW required for growth as the water-column light requirement (WCLR). In Equation IV-2 and the equations that follow, it should be understood that decimal fractions are being used for quantities such as PLW and WCLR, expressed as percentages (i.e. 22 percent=0.22). If WCLR is known, then the largest diffuse attenuation that would permit growth to depth=Z_{max} is given by

$$K_d = \ln(WCLR)/Z_{max} \qquad \text{(IV-3).}$$

Expressing K_d in Equation IV-3 as a function of the optically active water quality parameters forms the basis for the diagnostic tool for identifying a range of water quality conditions necessary for achieving the water-column light target.

PARTITIONING SOURCES OF WATER-COLUMN LIGHT ATTENUATION

Underwater light is attenuated by water itself and by certain dissolved and particulate substances. The optically important water quality parameters are colored dissolved organic matter or yellow substance (Kirk 1994), and suspended particulate matter. Suspended particulate matter can be further characterized by its contributions from fixed (i.e., noncombustible) suspended solids composed of clay, silt and sand mineral particles, and volatile (i.e., combustible) suspended solids composed of phytoplankton chlorophyll *a* and nonpigmented organic detritus. Each of the materials has characteristically shaped light absorption spectra. Because PAR is measured over a wide range of wavelengths, the spectral dependence of absorption means that the effect of one material, for example, phytoplankton, on light attenuation will depend on the concentrations of other materials present at the same time. For this and other reasons related to the nonlinearity of the radiative transport equations, the concept of a partial attenuation coefficient for the various optical water quality parameters is only an approximation, and one that has been criticized (Kirk 1994). In spite of these known limitations in partitioning the diffuse attenuation coefficient into contributions due to individual components, that approach is adopted here because of the need to derive a tool that is simple to use with large amounts of data and can be interpreted by managers unacquainted with the details of radiative transport theory.

First, the attenuation coefficient for downwelling (moving down through the water) light is expressed as the sum of that due to water (W) plus dissolved organic matter (DOC), phytoplankton chlorophyll *a* (Chl) and total suspended solids (TSS). Based on the analyses presented below, it is assumed that attenuation due to dissolved matter is relatively constant and may be included with water itself. We further assume that the contributions to light attenuation due to chlorophyll *a* and total suspended solids are proportional to their concentrations, so that the diffuse attenuation coefficient may be written as

$$K_d = K_{(W+DOC)} + k_c[Chl] + k_s[TSS] \qquad \text{(IV-4)}$$

where $K_{(W+DOC)}$ is the partial attenuation coefficient due to water plus colored dissolved matter, and k_c and k_s are the specific-attenuation coefficients due, respectively, to chlorophyll *a* and to total suspended solids. By combining equations IV-3 and IV-4, combinations of chlorophyll *a* and total suspended solids that just meet the WCLR may be calculated using:

$$\ln(WCLR)/Z_{max} = K_{(W+DOC)} + k_c[Chl] + k_s[TSS] \qquad \text{(IV-5).}$$

By assuming that $K_{(W+DOC)}$ is constant, Equation IV-6 can be used to calculate linear combinations of concentrations of total suspended solids and chlorophyll *a* that just meet the WCLR,

$$[TSS] = \{[\ln(WCLR)/Z_{max}] - K_{(W+DOC)}k_c[Chl]\}/k_s \quad \text{(IV-6).}$$

For a 1-meter colonization depth and PLW equaling 22 percent, $\ln(WCLR)/Z_{max}=1.51$. Parallel lines for other colonization depths are found by dividing ln(PLW) in Equation IV-5 by the appropriate value of Z_{max}. Adjustment of the colonization depth for tidal range is a simple but important modification presented in Chapter VI.

DIAGNOSTIC TOOL COEFFICIENTS

Application of the diagnostic tool requires values for three coefficients: the attenuation due to water plus dissolved matter, $K_{(W+DOC)}$, the specific-attenuation coefficients for phytoplankton chlorophyll, k_c, and total suspended solids, k_s. Initially, coefficients (including a separate specific-attenuation coefficient for dissolved organic carbon) were estimated by multiple linear regression of K_d (dependent variable, calculated from vertical profiles of underwater quantum sensor readings measured by the Chesapeake Bay Phytoplankton Monitoring Program) against dissolved organic carbon, chlorophyll *a* and total suspended solids (independent variables) measured through the Chesapeake Bay Water Quality Monitoring Program. Statistical summaries of the measured water quality parameters at stations for which light profiles were measured are reported in Table IV-1, and results of the linear regressions are given in Table IV-2.

Due to variability in the data, coefficients of determination were generally low, and occasionally (at five stations for k_c) negative specific-attenuation coefficients were calculated. Therefore, coefficients were selected using a combination of approaches in which coefficients estimated by linear regression with the Chesapeake Bay Monitoring Program data were first examined. The resulting linear regression estimates were compared with literature values where available, and refined using the optical model of Gallegos (1994), in which individual water quality parameters can be varied independently. Predictions made with the refined linear regression were again compared with measurements made through the Chesapeake Bay Water Quality Monitoring Program to correct for overall bias.

Water Alone

The attenuation due to water alone is taken to be the intercept of a regression of K_d against the three optical water quality parameters, dissolved organic carbon, chlorophyll *a* and total suspended solids. Intercepts in the regressions of K_d against dissolved organic carbon, chlorophyll *a* and total suspended solids ranged from 0.4 to 1.1 m^{-1} at mainstem Chesapeake Bay Water Quality Monitoring Program stations, and from 0.6 to 3.2 m^{-1} at tidal tributary Chesapeake Bay Water Quality Monitoring Program stations. In general, these are very high values and cannot represent the actual attenuation due to water itself that would occur if all other optically active constituents were removed.

Light absorption by pure water varies strongly over the visible spectrum, being minimal in the blue and increasing sharply at red wavelengths. Because of the spectral narrowing caused by the selective absorption of red wavelengths, the attenuation attributable to water itself varies strongly with the depth range considered (Morel 1988). Lorenzen (1972) estimated the attenuation due to water alone to be 0.038 m^{-1}, though his measurements were for deep ocean conditions, in which measurements generally commence at depths > 5 meters.

The optical model of Gallegos (1994) with water as the only factor contributing to attenuation predicts a range of K_W from about 0.16 to 0.13 m^{-1} as the depth is varied from 1 to 3 meters. Though the variation may seem small, the same model calculates Lorenzen's (1972) value of 0.038 m^{-1} for seawater over a 51-meter depth interval. Thus, in shallow water, the attenuation due to water itself is not negligible, though much smaller than the intercepts estimated by linear regression in Table IV-2. Evidently, the regressions lump much unexplained variance into the intercept.

Dissolved Organic Carbon

Statistically significant coefficients for specific attenuation of dissolved organic carbon were obtained at only two stations, giving specific-attenuation coefficients of 0.09 and 0.2 $m^2\ g^{-1}$ (Table IV-2). The overall coefficient of determination and accompanying

TABLE IV-1. Statistical summaries of concentrations of optical water quality parameters—chlorophyll, dissolved organic carbon and total suspended solids for Chesapeake Bay Water Quality Monitoring Program stations at which underwater light measurements were made.

Station	Number of Observations	Mean	Median Derivation	Standard	Minimum	Maximum
			CHESAPEAKE BAY MAINSTEM STATIONS			
Chlorophyll (μg/L)						
CB1.1	164	8.28	7.60	6.38	1.00	52.0
CB2.2	174	5.03	3.62	4.51	1.00	27.9
CB3.3C	177	15.5	11.6	15.7	1.00	105
CB4.3C	176	8.10	7.20	4.36	1.70	24.4
CB5.2	176	9.44	7.05	8.01	1.10	44.0
Dissolved Organic Carbon (mg/L)						
CB1.1	165	2.68	2.61	0.656	1.26	5.88
CB2.2	170	2.76	2.71	0.558	1.60	5.87
CB3.3C	174	2.79	2.71	0.427	0.820	4.07
CB4.3C	173	2.85	2.74	0.667	2.09	8.97
CB5.2	175	2.95	2.78	0.744	2.13	8.86
Total Suspended Solids (mg/L)						
CB1.1	174	10.8	7.18	12.8	1.50	108
CB2.2	175	16.9	14.7	11.0	1.85	87.3
CB3.3C	180	7.61	6.85	3.79	2.50	29.9
CB4.3C	179	4.59	4.40	1.33	1.60	10.3
CB5.2	181	4.91	4.50	1.80	1.50	11.5
			TIDAL TRIBUTARY STATIONS			
Chlorophyll (μg/L)						
MEE3.1	5	4.72	4.69	2.15	1.82	7.79
MET4.2	7	9.26	9.12	1.92	6.94	12.71
MET5.1	141	49.6	31.80	56.29	4.58	391.2
MET5.2	137	12.05	9.64	10.30	0.83	66.18
MLE2.2	147	14.7	11.4	11.9	2.18	

continued

TABLE IV-1. Statistical summaries of concentrations of optical water quality parameters—chlorophyll, dissolved organic carbon and total suspended solids for Chesapeake Bay Water Quality Monitoring Program stations at which underwater light measurements were made (*continued*).

Station	Number of Observations	Mean	Median Derivation	Standard	Minimum	Maximum
MWT5.1	141	49.6	31.8	56.3	4.58	391
PXT0402	150	40.3	35.7	30.3	0.260	126
XDA1177	129	6.89	4.38	7.70	0.880	43.8
XDE5339	158	19.3	15.3	18.7	2.57	189
XEA6596	90	16.0	9.72	16.4	0.430	71.4
XED4892	89	14.0	11.7	13.9	0	122
Dissolved Organic Carbon (mg/L)						
MEE3.1	5	3.52	3.58	0.155	3.25	3.63
MET4.2	7	2.76	2.78	0.200	2.41	3.01
MET5.1	138	6.13	5.83	2.25	0.820	19.7
MET5.2	105	3.85	3.62	1.27	1.70	8.73
MLE2.2	110	3.33	3.27	1.22	0.820	7.84
MWT5.1	110	3.46	3.26	1.35	0.780	6.97
PXT0402	147	4.67	4.69	1.07	1.11	8.10
XDA1177	54	3.99	3.69	1.21	1.42	7.54
XDE5339	136	3.16	3.13	0.725	1.22	5.90
XEA6596	60	3.86	3.73	1.09	1.67	7.25
XED4892	86	4.52	4.50	0.854	2.27	7.09
Total Suspended Solids (mg/L)						
MEE3.1	5	13.2	16	10.6	2	27
MET4.2	7	6.57	7	3.87	1	12
MET5.1	143	33.1	30.5	17.1	5	96
MET5.2	138	13.8	12.2	9.00	1	52
MLE2.2	147	11.8	11	6.81	1	40
MWT5.1	142	17.3	15	11.3	1	58
PXT0402	152	36.1	33	19.1	1	156
XDA1177	130	20.1	18	11.5	3.5	71
XDE5339	158	11.3	9.62	6.03	1	39
XEA6596	93	19.1	17	9.37	2	51
XED4892	89	34.2	29.3	20.6	9.5	136

TABLE IV-2. Coefficients (an estimate of specific-attenuation coefficient) and intercepts (an estimate of attenuation due to water alone) estimated by linear regression of diffuse attenuation coefficient, K_d (dependent variable), against concentrations of dissolved organic carbon, phytoplankton chlorophyll and total suspended solids. Data from Chesapeake Bay Water Quality Monitoring Program, but limited to stations at which underwater light measurements were made. ns = not statistically significant, $P>0.05$.

Station	Coefficient of Determination	Degrees of Freedom	Intercept	Dissolved Organic Carbon (m^2g^{-1})	Phytoplankton Chlorophyll (m^2mg^{-1})	Total Suspended Solids (m^2g^{-1})
Mainstem Chesapeake Bay						
CB1.1	0.569	104	0.581	0.1015 ns	0.0022 ns	0.101
CB2.2	0.528	117	1.143	-0.0100 ns	-0.0082 ns	0.074
CB3.3C	0.453	129	0.610	0.0142 ns	-0.0012 ns	0.076
CB4.3C	0.148	121	0.533	-0.0091 ns	0.0192	0.041
CB5.2	0.271	121	0.393	0.0209 ns	0.0105	0.042
Tidal Tributaries						
MET5.1	0.208	96	3.227	0.1960	-0.0236	0.033
MET5.2	0.378	80	0.605	0.0931	0.0170	0.013
MWT5.1	0.530	78	1.581	-0.0493 ns	0.0108	-0.001 ns
PXT0402	0.109	104	2.833	0.3065 ns	-0.0113 ns	0.043
XDA1177	0.338	42	1.327	0.0695 ns	-0.0153 ns	0.047
XDE5339	0.219	100	0.807	0.0409 ns	0.0048 ns	0.042
XEA6596	0.321	47	1.271	0.0074 ns	0.0020 ns	0.064
XED4892	0.463	71	2.096	0.1225 ns	-0.0461	0.058

coefficients for specific-attenuation of total suspended solids were anomalously low at these two tidal tributary stations, casting doubt on the reliability of these values.

Only a variable fraction of dissolved organic carbon, referred to as colored dissolved organic matter, contributes to light attenuation (Cuthbert and del Giorgio 1992). Therefore, the lack of statistically significant coefficients at most stations is not surprising. Colored dissolved organic matter absorbs light but does not contribute appreciably to scattering (Kirk 1994). In the PAR waveband, absorption by colored dissolved organic matter is maximal in the blue region of the spectrum and decreases exponentially with wavelength. Optically, the effect of colored dissolved organic matter on attenuation is best quantified by the absorption coefficient of filtered estuary water (0.2 or 0.4 mm membrane filter) at a characteristic wavelength, which, by convention, is most often 440 nm (Kirk 1994).

In an effort to quantify the contribution of colored dissolved organic matter to attenuation, the regression of Gallegos *et al.* (1990) between absorption coefficient (corrected to 440 nm) and dissolved organic carbon was incorporated into the model of Gallegos (1994). Water quality conditions for other parameters, chlorophyll *a* and total suspended solids, were chosen to represent average conditions for a range of water quality monitoring stations along the upper length of the mainstem Chesapeake Bay (Table IV-1).

The specific attenuation coefficient of dissolved organic carbon calculated by the model varied from 0.026 m^2 g^{-1} for upper Bay tidal fresh conditions to 0.031 m^2 g^{-1} for lower Bay mesohaline conditions. Concentrations of dissolved organic carbon were surprisingly uniform along the axis of the mainstem Chesapeake Bay, ranging from about one to six mg $liter^{-1}$ in the upper Chesapeake Bay to two to nine mg $liter^{-1}$ at station CB5.2, located in the mainstem Chesapeake Bay off the mouth of the Potomac River (Table IV-1). The contribution of dissolved organic carbon to light attenuation can, therefore, be expected to average about 0.07 m^{-1} and range from about 0.03 to 0.23 m^{-1}. The average contribution of dissolved organic carbon to light attenuation is less than that of water itself (i.e., >0.13 m^{-1}, see above) in shallow systems and therefore can be expected to be difficult to detect in monitoring data, which are subject to expected levels of sampling and analytical error.

Therefore, as discussed above, the effect of dissolved organic carbon was incorporated into the regression for K_d as a constant term lumped in with the attenuation due to water itself. It must be recognized that this approximation will not be applicable to tidal tributaries with high concentrations of humic-stained water, such as the Pocomoke River. Site-specific approaches will be needed to tailor the diagnostic tool for such systems, including collection of optically relevant water quality data, namely absorption by dissolved matter at 440 nm (ideally) or color in Pt. units.

A trial value for the combined attenuation due to water and dissolved organic carbon, $K_{(W+DOC)}$, was determined by setting total suspended solids and chlorophyll *a* concentrations in the model of Gallegos (1994) to zero, and allowing concentrations of dissolved organic carbon to vary according to a normal distribution with mean of 2.71 mg $liter^{-1}$ and standard deviation of 0.44 mg $liter^{-1}$, similar to observations at Chesapeake Bay Water Quality Monitoring Program station CB3.3C (Table IV-1). Attenuation due to water and dissolved organic carbon calculated in this manner varied from 0.21 to 0.31 m^{-1} and averaged 0.26 m^{-1}, which was used as a trial value.

Phytoplankton Chlorophyll

Phytoplankton, being pigmented cells (i.e., particles), contribute both to absorption and the scattering of light. Light absorption by phytoplankton varies strongly with wavelength. The shape of the *in vivo* absorption spectrum of phytoplankton varies with species, but generally, peaks occur at about 430 nm and at 675 nm, with a broad minimum in the green region of the spectrum (Jeffrey 1981). Because of this spectral dependence, the contribution of phytoplankton to attenuation varies with the depth and composition of the water (Atlas and Bannister 1980), and to a lesser extent in natural populations, with species composition.

By linear regression on data from the Chesapeake Bay Water Quality Monitoring Program, statistically significant estimates for the specific-attenuation coefficient for chlorophyll *a* were obtained at 6 of 13 stations (Table IV-2). Two of those were negative values and must be considered spurious. Significant positive values ranged from 0.011 to 0.019 m^2 (mg Chl)$^{-1}$. This range compares favorably with values reported in the literature. For example, Atlas and Bannister (1980) used a fixed specific absorption spectra and calculated a range of the chlorophyll-specific attenuation coefficients near the surface ranging between 0.013 and 0.016 m^2 (mg Chl)$^{-1}$. The overall magnitude of the chlorophyll-specific absorption spectrum, however, varies considerably with physiological state, photoadaptation, and recent history of light exposure of the phytoplankton population. A wider survey of the literature, reviewed by Dubinsky (1980) suggested values between 0.005 and 0.040 m^2 (mg Chl)$^{-1}$, but most estimates range more narrowly between 0.01 to 0.02 m^2 (mg Chl)$^{-1}$ (Lorenzen 1972; Smith and Baker 1978; Smith 1982; Priscu 1983).

Model-generated estimates of k_c can be similarly variable. The effect of chlorophyll *a* on K_d is incorporated in the optical model through the chlorophyll-specific absorption spectrum. The coefficient of variation in measured chlorophyll-specific absorption spectra in the Rhode River was about 50 percent (Gallegos 1994) and overall range varied by about a factor of four (Gallegos *et al.* 1990). When this degree of variability in the chlorophyll-specific absorption spectrum is incorporated into the optical model of Gallegos (1994), calculated k_c range from <0.01 to 0.035 m^2 (mg chl)$^{-1}$, with an average of about 0.016 m^2 (mg Chl)$^{-1}$. Therefore, an initial estimate for k_c of 0.016 m^2 (mg Chl)$^{-1}$ was chosen. This value is near the center of the observed range and is commensurate with the optical water quality model and literature estimates (Bannister 1974; Smith and Baker 1978; Priscu 1983).

Total Suspended Solids

Statistically significant estimates for the specific-attenuation coefficient for total suspended solids were obtained by the linear regression analysis at all but one station (Table IV-2). Values for k_s ranged from 0.013 to 0.101 m^2 g^{-1}. Because of the wide range of coefficients and because the lower values (< 0.05 m^2 g^{-1}) were generally associated with lower coefficients of determination (Table IV-2), literature and model-generated values for k_s were also examined.

Literature estimates of k_s in estuaries tend to cluster around the middle of the range estimated from the Chesapeake Bay Water Quality Monitoring Program data. For example, Cloern (1987) estimated k_s of 0.06 m^2 g^{-1} for San Francisco Bay, similar to Malone's (1976) value for the New York Bight. Pennock (1985) estimated a specific-attenuation coefficient of 0.075 m^2 g^{-1} in the Delaware Estuary, similar to two of the mainstem Chesapeake Bay water quality stations (Table IV-2). Verduin (1964; 1982 cited in Priscu 1983) found k_s averaged 0.12 m^2 g^{-1} for a number of river-dominated freshwater systems, similar to the regression estimate for upper Chesapeake Bay station CB1.1 (Table IV-2).

The optical model of Gallegos (1994) accounts for the combined effects of scattering and absorption by suspended particulate matter using the equations of Kirk (1984). As discussed above, scattering contributes to light attenuation by increasing the path length that light travels, thereby increasing the probability of absorption. Direct measurement of scattering is difficult; but by fortunate coincidence, the turbidity of a water sample measured in nephelometric turbidity units (NTU) using commercially available turbidimeters has been shown to be a good estimate of scattering coefficient in relatively turbid waters, including estuaries, by a number of authors (Kirk 1981; Oliver 1990; Di Toro 1978; Vant 1990). Operationally, this is understandable from the manner in which a turbidimeter works, i.e., by measuring the intensity of light scattered at 90 degrees from a beam shone upward through the bottom of the sample. That the units of the measurement should scale with scattering coefficient is, however, serendipitous (Kirk 1981).

Turbidity has not been routinely monitored in the Chesapeake Bay Water Quality Monitoring Program. Measurements in two systems, the Rhode River, Maryland, a Chesapeake Bay tidal tributary, and Chincoteague Bay, a coastal lagoon on the Maryland-Virginia border, indicate that scattering in both systems is strongly dominated by the mass concentration of suspended solids (Figure IV-1A). The relationship between turbidity and total suspended solids in the two systems was nearly identical, despite a much greater contribution of chlorophyll *a* to the suspended material in the Rhode River (Figure IV-1B) (Gallegos 1994). Evidently, phytoplankton contribute to scattering on a dry-weight basis approximately as much as inorganic suspended solids and organic detritus. The generality of these observations is uncertain. It is likely that relationships as precise as these would be difficult to obtain if the geographic extent or length of time

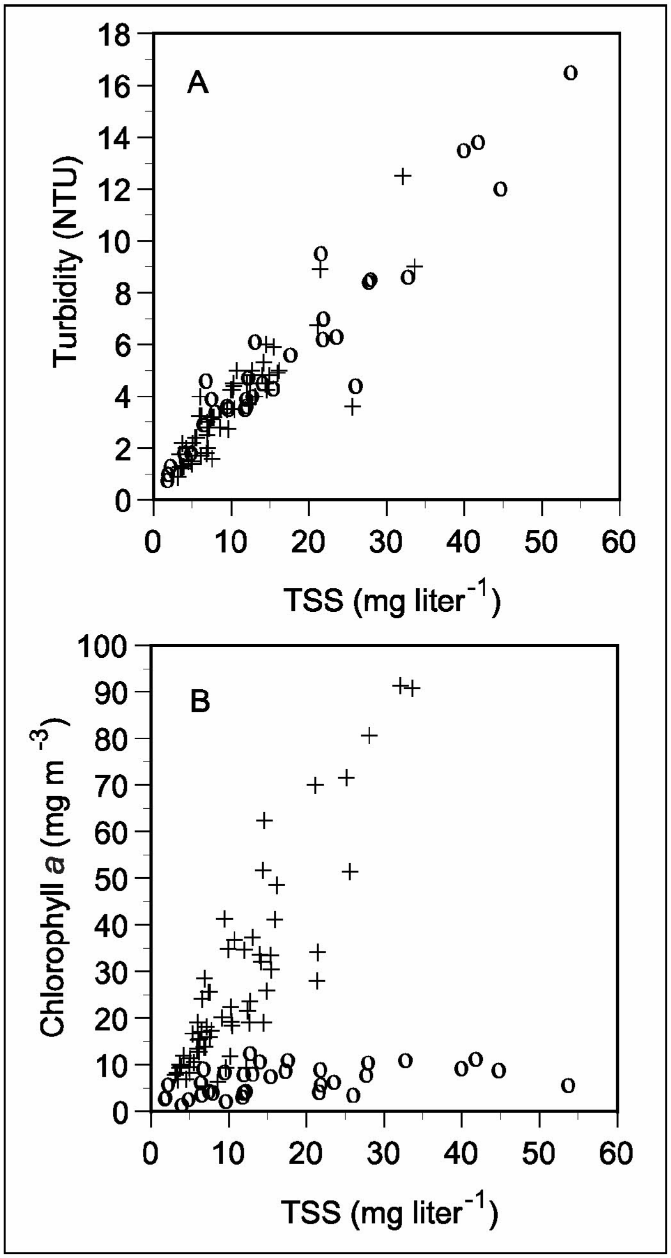

FIGURE IV-1. Relationship of Turbidity and Chlorophyll to Total Suspended Solids: Rhode River and Chincoteague Bay. This figure illustrates the relationship between turbidity (an estimate of scattering coefficient, see text) and total suspended solids (TSS) in (+) the Rhode River, Maryland, a tributary sub-estuary of Chesapeake Bay, and in (o) Chincoteague Bay, a coastal lagoon (A). Despite similar relationships between turbidity and TSS, the Rhode River and Chincoteague Bay contrast in their composition of TSS; chlorophyll contributes a much greater proportion to TSS in the Rhode River than in Chincoteague Bay (B).

covered were increased, and different instruments and standards were employed.

The spectral specific-absorption curves of suspended solids, including both inorganic silts and clays and organic detritus, typically have a negative exponential shape similar to that of dissolved organic matter (Kirk 1994). A single curve was sufficient to model absorption by non-algal turbidity in the Rhode River and Chincoteague Bay, Maryland (Gallegos 1994), but different site-specific curves were needed in the Indian River Lagoon, Florida (Gallegos and Kenworthy 1996). Overall, the spatial variability of absorption by non-algal suspended particulate matter has not been well studied.

With absorption and scattering accounted for in the optical model (Gallegos 1994), the specific-attenuation coefficient for total suspended solids was calculated by making small increments in total suspended solids concentrations, as was done above for dissolved organic carbon. The resulting value for k_s was 0.072 m^2 g^{-1}, with only minor dependence on other water quality parameters. This value is very similar to literature estimates, although the calculation is based on a single specific-absorption curve and does not take into account possible changes in the specific-absorption curve caused by potential variations in the mineralogical or humic content of soils around the Bay region. Based on the similarity of literature and model estimates, an initial estimate for k_s of 0.074 m^2 g^{-1} was selected.

EVALUATION OF THE K_d REGRESSION

Based on the initial selections of specific-attenuation coefficients, the predicted diffuse-attenuation coefficients from Chesapeake Bay Water Quality Monitoring Program data are given by the linear regression

$$K_d = 0.26 + 0.016[\text{Chl}] + 0.074[\text{TSS}] \qquad \text{(IV-7).}$$

An examination of the predicted values against measured values (Figure IV-2) showed a tendency for the regression to underestimate measured K_d at both mainstem Bay (Figure IV-2A) and tidal tributary (Figure IV-2B) water quality monitoring stations. At mainstem Chesapeake Bay water quality monitoring stations there appeared to be bias in the slope of predicted against observed, whereas at tidal tributary stations there appeared to be an offset as well. By trial

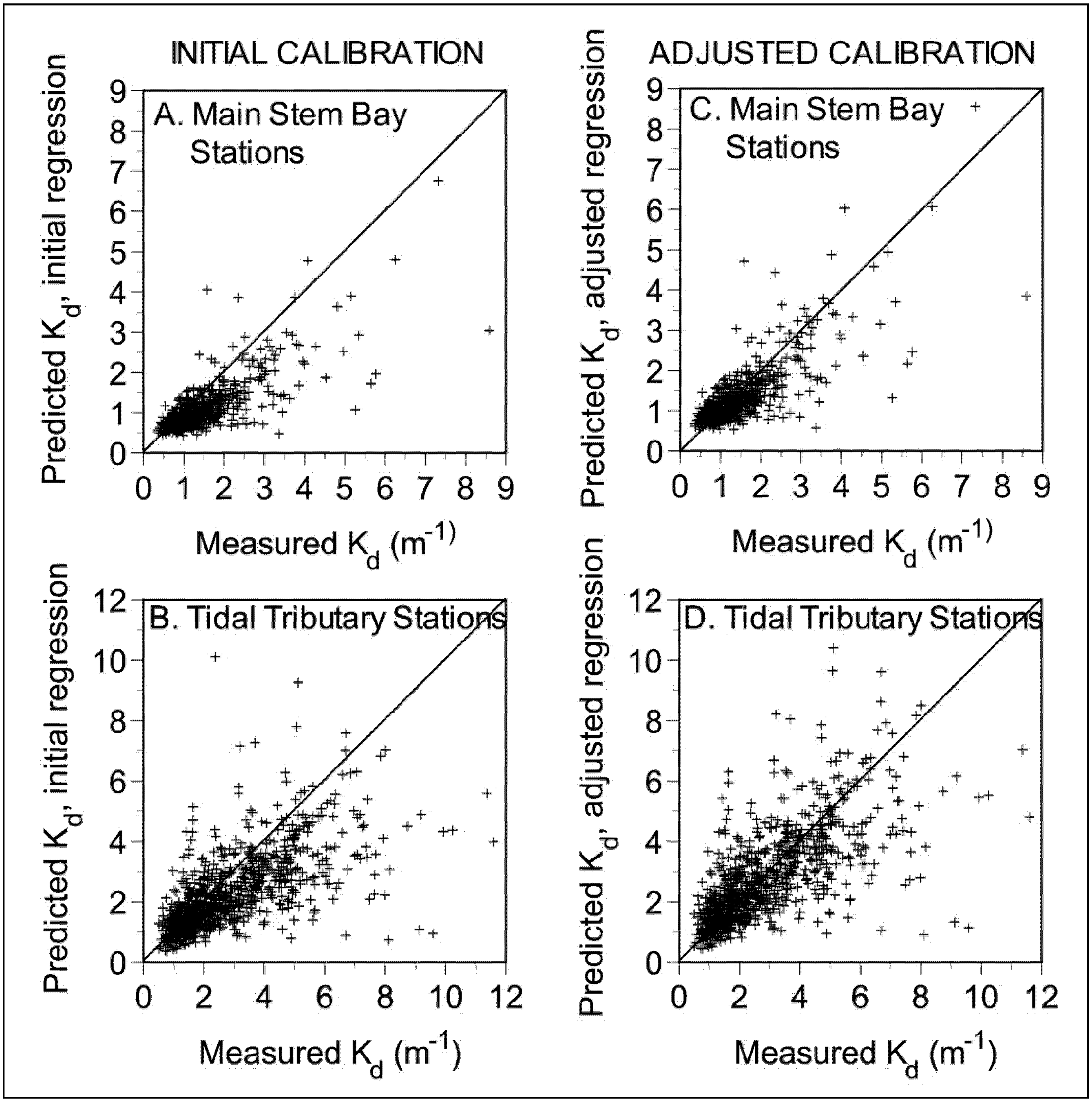

FIGURE IV-2. Comparison of Measured K_d with Predictions by Linear Regression Model. Comparison of measurements of diffuse attenuation coefficient (K_d) made in the Chesapeake Bay Water Quality Monitoring Program (1986-1996) with predictions made by linear regression against optical water quality parameters. (A) and (B) are predictions based on initial estimates of coefficients (Equation IV-7); (C) and (D) are predictions based on Equation IV-8, in which attenuation due to water plus dissolved organic carbon and partial attenuation coefficient of total suspended solids were adjusted upward. (A) and (C) are data from mainstem Chesapeake Bay stations; (B) and (D) are data from Maryland tidal tributary stations.

and error, predictions were improved by adjusting the estimated $K_{(W+DOC)}$ to 0.32 m^{-1} and the specific-attenuation coefficient of total suspended solids to 0.094 m^2 g^{-1} (Figure IV-2C, -2D), possibly indicating that the highest attenuation coefficients are dominated by times and locations of highest river flows. These modifications result in a final regression model of

$$K_d = 0.32 + 0.016[Chl] + 0.094[TSS] \qquad (IV\text{-}8).$$

Overall, the scatter in these plots indicates that more sophisticated models cannot be considered, given the limited amount of optical information in the data that are available. The r^2 for the final fits are 0.61 for mainstem Chesapeake Bay stations, and only 0.37 for tidal tributary stations. It is also likely that site-specific coefficients for k_s and possibly $K_{(W+DOC)}$ will be needed as a future refinement. Present experience with regressions on the monitoring data (Table IV-2) indicate that site-specific refinements to coefficients will need to be computed from optical modeling, based on direct determination of specific-absorption and specific-scattering spectra of total suspended solids from a wide range of sites around the Bay.

With these coefficients, Equation IV-6 can be used to write equations for combinations of chlorophyll *a* and total suspended solids that meet the WCLR for depths of 0.5, 1.0 and 2.0 meters. For mesohaline and polyhaline habitats where WCLR = 0.22 (22 percent, from Chapter III), the equations are

$$0.5\text{ m}\ \ [TSS] = 28.8\ 0.17[Chl],\ [Chl] < 169.4 \qquad (IV\text{-}9a)$$

$$1.0\text{ m}\ \ [TSS] = 12.7\ 0.17[Chl],\ [Chl] < 74.7 \qquad (IV\text{-}9b)$$

$$2.0\text{ m}\ \ [TSS] = 4.65\ 0.17[Chl],\ [Chl] < 27.4 \qquad (IV\text{-}9c)$$

where the upper bound on [Chl] is the chlorophyll *a* concentration at which the predicted [TSS] = 0 for that depth; that is, higher chlorophyll *a* concentrations would result in a prediction of a 'negative concentration' for [TSS].

Comparable equations for tidal fresh and oligohaline habitats are determined by substituting 0.13 (13 percent from Chapter III) for WCLR in Equation IV-6,

$$0.5\text{ m}\ [TSS] = 40.0 - 0.17[Chl],\ [Chl] < 235 \qquad (IV\text{-}10a)$$

$$1.0\text{ m}\ [TSS] = 18.3 - 0.17[Chl],\ [Chl] < 107 \qquad (IV\text{-}10b)$$

$$2.0\text{ m}\ [TSS] = 7.45 - 0.17[Chl],\ [Chl] < 43.8 \qquad (IV\text{-}10c).$$

COMPONENTS OF TOTAL SUSPENDED SOLIDS

Total suspended solids consist of the dry weight of all particulate matter in a sample, including clay, silt and sand mineral particles, living phytoplankton and heterotrophic plankton, including bacteria and particulate organic detritus. Therefore, phytoplankton and the heterotrophic community it supports contribute to what is measured by total suspended solids. As shown above, optically it is difficult to distinguish the effect of particulate organic matter, including that contributed by phytoplankton, from that of mineral particulates. Nevertheless, it is useful to examine their relative contributions to the measurement of total suspended solids, since organic particulates (due, in part, to nutrient over-enrichment) must be controlled differently than mineral particulates (due, in part, to erosion or sediment resuspension). In particular, a reduction in chlorophyll *a* will be accompanied by a proportional reduction in total suspended solids due to the dry weight component of phytoplankton. This additional reduction in total suspended solids needs to be incorporated into the predicted response of K_d when using equations (IV-9a-c) for determining the water quality conditions necessary for achieving the minimum light requirements.

Upon combustion, the particulate organic matter in a sample is oxidized, leaving behind the mineral component and ash of the organic fraction. The fraction remaining after combustion is referred to as fixed suspended solids (FSS), and the difference between the total and the fixed fraction of suspended solids is called total volatile suspended solids (TVSS). The percentage of total suspended solids that is of organic origin can then be estimated as TVSS/TSS*100.

Fixed suspended solids and total volatile suspended solids have been measured at the Virginia tidal tributary and mainstem stations of the Chesapeake Bay Water Quality Monitoring Program. At very high concentrations of total suspended solids, total volatile suspended solids appears to approach a relatively constant fraction, about 18 percent, of total suspended solids (Figure IV-3). The extremely high concentrations probably represent flood conditions, and the fraction of total volatile suspended solids in those samples are probably characteristic of the terrestrial soils. At more realistic total suspended solids concentrations, i.e., those < 50 mg $liter^{-1}$, a much wider range in the percentage of total volatile suspended solids is observed (Figure IV-3, inset), exceeding 90 percent in some samples.

The relationship between total volatile suspended solids and particulate organic carbon shows a great deal of scatter (Figure IV-4A) but on average, particulate organic carbon is about 30 percent of total volatile suspended solids. This estimate is larger than that of living phytoplankton (26 percent) (Sverdrup *et al.* 1942) and lower than that of carbohydrate (37 percent). The particulate organic carbon in a sample consists of living phytoplankton, bacteria, heterotrophic plankton, their decomposition products, organic detritus from marshes or terrestrial communities and resuspended SAV detritus. As expected, a plot of particulate organic carbon against phytoplankton chlorophyll *a* displays considerable scatter (Figure IV-4B), but during sudden phytoplankton blooms, phytoplankton might comprise the major component of carbon in a sample. The ratio of carbon to chlorophyll *a* in

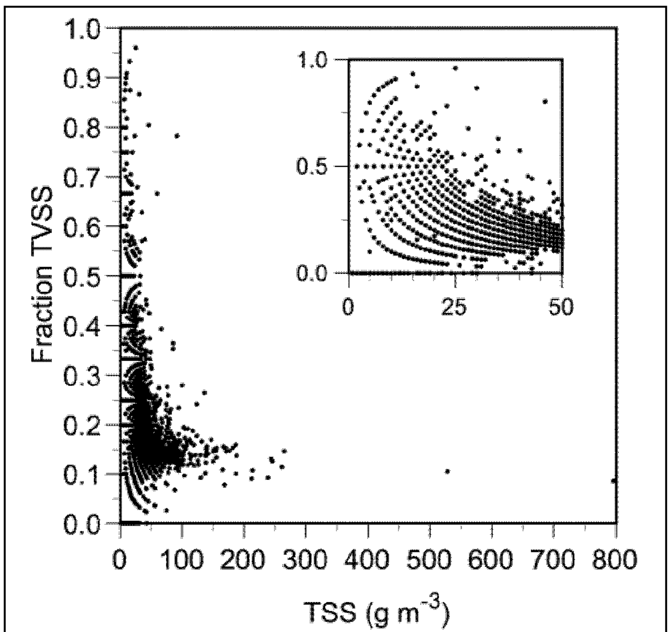

FIGURE IV-3. Fraction of Total Suspended Solids Lost on Ignition. Fraction of total suspended solids (TSS) that is lost on ignition as a function of TSS. At concentrations of TSS < 50 mg liter^{-1} (inset), the fraction of TSS that is volatile varies from 0 to >90 percent. Total volatile suspended solids (TVSS) calculated as total suspended solids minus fixed suspended solids, that is, the mass remaining after combustion. Fraction total volatile suspended solids calculated as total volatile suspended solids divided by total suspended solids. Data from Chesapeake Bay Water Quality Monitoring Program, Virginia tidal tributary stations, 1994-1996.

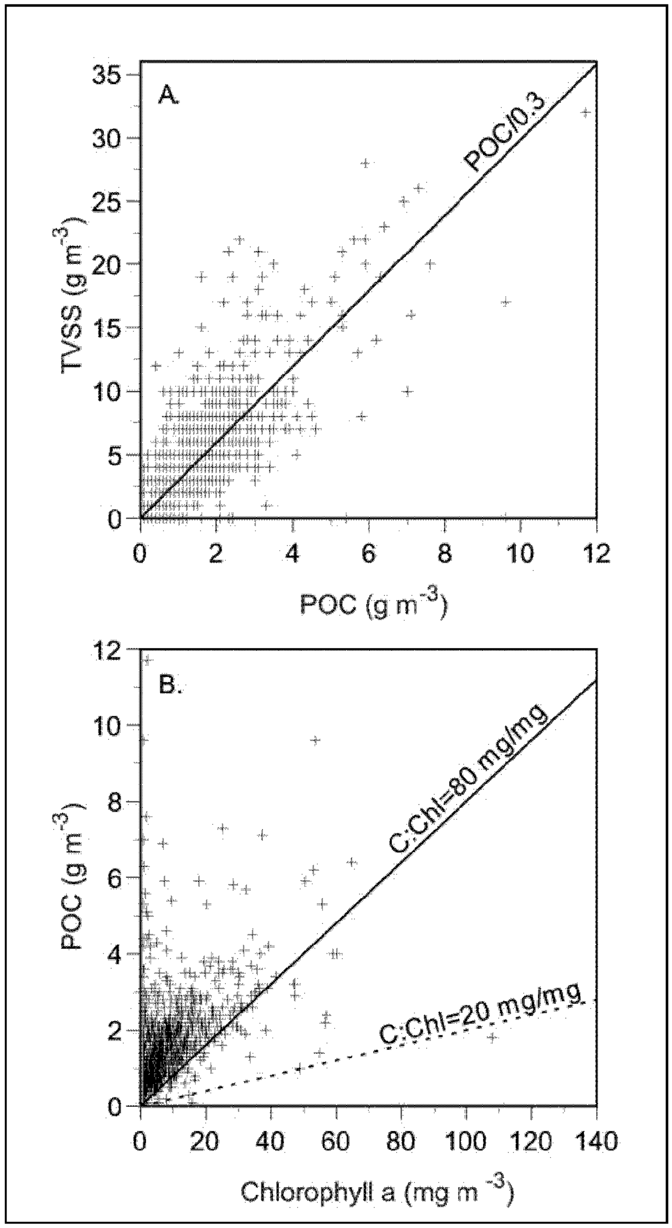

FIGURE IV-4. Relationships of Total Volatile Suspended Solids, Particulate Organic Carbon and Chlorophyll. Concentration of total volatile suspended solids (TVSS) as a function of particulate organic carbon (POC) for Virginia tidal tributary stations, 1994-1996. Line shows estimate of TVSS as POC/0.3 (A). Relationship of particulate organic carbon to chlorophyll concentration for Virginia tidal tributary stations (B). Lines bracket approximate contribution of phytoplankton to POC based on a range of phytoplankton carbon:chlorophyll ratios from 20 (dashed line) to 80 mg C (mg chlorophyll)$^{-1}$(solid line).

phytoplankton varies widely (Geider 1987). A range of about 20 to 80 mg C (mg chl)$^{-1}$ provides a lower bound of most of the points in Figure IV-4B, and this range is well within the physiological limits of phytoplankton (Geider 1987). Choosing 40 mg C (mg chl)$^{-1}$—the geometric mean of 20 and 80–as a representative carbon:chlorophyll *a* ratio, and using the 30 percent particulate organic carbon:total volatile suspended solids ratio from Figure IV-4A, the minimum contribution of phytoplankton chlorophyll *a* to total volatile suspended solids, designated ChlVS, is estimated as

$$\mathrm{ChlVS} = 0.04[\mathrm{Chl}]/0.3 \qquad \text{(IV-11)}$$

where the 0.04 results from the conversion of μg to mg chlorophyll liter^{-1}. Thus, although the optical effects of particulate organic detritus cannot be distinguished from that of mineral particles, the minimum contribution of phytoplankton to the measurement of total suspended solids is approximately given by ChlVS. This also implies that management action to reduce the concentration of chlorophyll *a* at a site will also result in a reduction of total suspended solids by an amount approximated by ChlVS. The actual reduction may be larger if a substantial heterotrophic community and the organic detritus generated by it are simultaneously reduced. This observation has significant implications for the implementation of site specific management approaches.

SUMMARY OF THE DIAGNOSTIC TOOL

The exponential decline of light intensity under water (Equation IV-1) allows for the percentage of surface light penetrating to a given depth to be written as a simple function of the diffuse attenuation coefficient (Equation IV-2). Equation IV-4 expresses in a general (albeit approximate) way the relationship between the diffuse-attenuation coefficient and the concentrations of optical water quality parameters. Once the SAV minimum light requirement and the SAV restoration depth are specified, Equation IV-4 may be rearranged to predict the concentrations of total suspended solids and chlorophyll *a* that exactly meet the water-column light requirement (Equation IV-6). Equations IV-9a-c express these water quality relationships for mesohaline and polyhaline regions for three depth ranges, and in terms of the specific-attenuation coefficients estimated for Chesapeake Bay from the literature, by optical modeling and by analysis of data from the Chesapeake Bay Water Quality Monitoring Program. Equations IV-10a-c express the same relationships for tidal fresh and oligohaline regions. Equation IV-11 estimates an approximate minimum concentration of total suspended solids attributable to phytoplankton. Equation IV-11 is used to better predict the reduction in total suspended solids, and, therefore, the diffuse attenuation expected to occur when the chlorophyll *a* concentration is reduced.

APPLICATION OF THE DIAGNOSTIC TOOL

A plot of measured total suspended solids against chlorophyll *a* concentrations from a given station in relation to lines defined by equations IV-9a-c demonstrates the extent to which the water-column light requirement is met at that location. In addition, a line representing Equation IV-11 shows the minimum contribution of chlorophyll *a* to total suspended solids at the location. Three examples from the Chesapeake Bay Water Quality Monitoring Program demonstrate information that may be determined by examining plots of total suspended solids against chlorophyll *a* in relation to the restoration depth-based water-column light requirements (Figure IV-5).

Suspended Solids Dominant Example

At station CB2.2, located in the upper Chesapeake Bay mainstem near the turbidity maximum, total suspended solids dominates the variability in light attenuation (Figure IV-5A). The median water quality concentrations fail to meet the 1-meter water-column light requirement, and the predominant direction of variability in the scatter of individual data points is vertical, i.e., parallel to the total suspended solids axis. Stations characterized by elevated total suspended solids and low chlorophyll *a* indicate cases in which suspended solids dominate the variation in light attenuation. Depending upon site-specific factors, the source of suspended solids may be due to land-based erosion, channel scour and/or the resuspension of bottom sediments due to winds or currents. When measurements are principally parallel to the total suspended solids axis, reductions in total suspended solids will be needed to achieve light conditions for SAV survival and growth.

Phytoplankton Bloom Example

Variations in chlorophyll *a* dominate the variability in attenuation at tidal tributary Chesapeake Bay Water

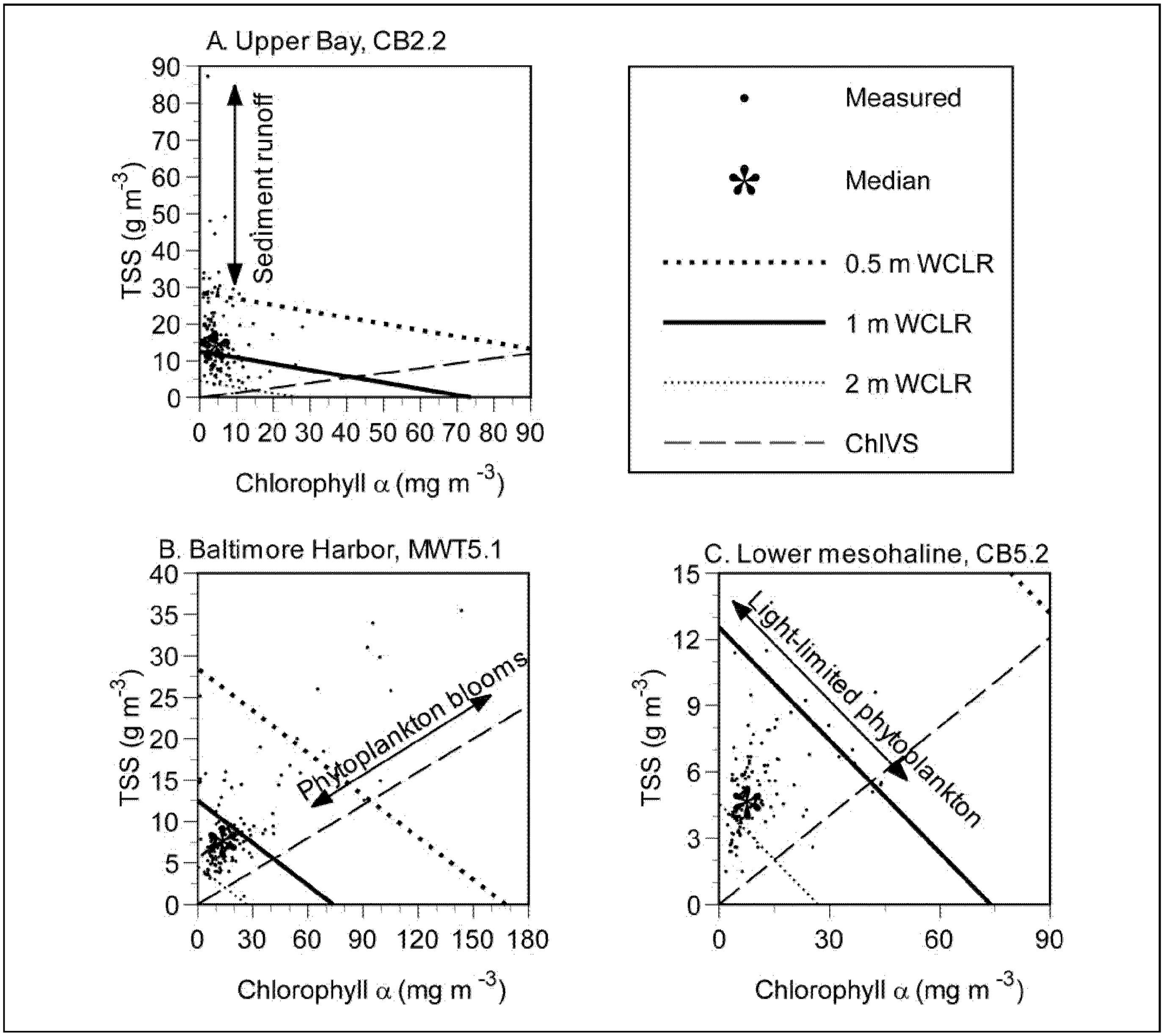

FIGURE IV-5. Application of the Diagnostic Tool Illustrating Three Primary Modes of Variation in the Data. Application of diagnostic tool to two mainstem Chesapeake Bay stations and one tributary station, which demonstrate three primary modes of variation in the data: (A) variation in diffuse attenuation coefficients is dominated by (flow related) changes in concentrations of total suspended solids (TSS) (upper Bay station CB2.2); (B) variation in attenuation coefficients is dominated by changes in chlorophyll concentration (Baltimore Harbor, MWT5.1); and (C) maximal chlorophyll concentration varies inversely with TSS indicative of light-limited phytoplankton. Plots show (points) individual measurements and (asterisk) growing season median in relation to the water-column light requirements (WCLR) for restoration to depths of 0.5 m (short dashes), 1.0 m (solid line), and 2.0 m (dotted line); water-column light requirements calculated by equations IV-9a-c (see text). Note the change in scale. Approximate minimum contribution of chlorophyll to TSS (ChlVS) is calculated by Equation IV-11 (long dashes). Data from Chesapeake Bay Water Quality Monitoring Program, April through October, 1986-1996.

Quality Monitoring Program station MWT5.1 in Baltimore Harbor, Maryland (Figure IV-5B). Median concentrations indicate that conditions for growth of SAV to the 1-meter depth are met, but many individual points violate both the 1-meter and 0.5-meter water-column light requirements (Figure IV-5B). The main orientation of points that violate 1-meter and 0.5-meter water-column light requirements is parallel to the ChlVS line (Figure IV- 5B, long dashes). Stations with elevated chlorophyll *a* concentrations that exhibit variability parallel to the ChlVS line can be classified as nutrient-sensitive, because attenuation is often dominated by phytoplankton blooms, indicating a susceptibility to eutrophication. Reduction of chlorophyll *a* concentrations would simultaneously reduce total suspended solids, moving the system parallel to the ChlVS line.

Light-Limited Phytoplankton Example

Another recognizable pattern exhibited in the data is an apparent upper bound of total suspended solids and chlorophyll *a* concentrations, aligned parallel to the water-column light requirements seen at mainstem Chesapeake Bay Water Quality Monitoring Program station CB5.2 (Figure IV-5C). Such behavior indicates that the maximal phytoplankton chlorophyll *a* concentrations are dependent on total suspended solids concentrations, and that the phytoplankton are light-limited (i.e., nutrient-saturated). Under those conditions, reducing suspended solids concentrations alone would not improve conditions for SAV, since phytoplankton chlorophyll *a* would increase proportionately to maintain the same light availability in the water column. This process is well-described by Wofsy's model (1983), in which water-column or mixing-layer depth is an important parameter. Application of Wofsy's (1983) Equation 17 with the specific-attenuation coefficients in Equation IV-7 (above) suggests that the community exhibits nutrient-saturated behavior with a mixing depth of 6 to 7 meters. The data indicate that conditions for growth of SAV to 1 meter are nearly always met at CB5.2, but if water with these properties were advected to shallower areas and maintained sufficient residence time there, it would support higher chlorophyll *a* concentrations.

It is, of course, possible for a system to display all three modes of behavior at a given location, particularly where there is strong seasonal riverine influence. For example, high total suspended solids and low chlorophyll *a* might be observed at spring flooding; nutrient-saturated behavior might occur as total suspended solids concentrations decline after spring floods subside; and blooms aligned parallel to the ChlVS line could occur in response to episodic inputs of nutrients at other times. Alignment along any of the trajectories described need not occur as a sequence in time. That is, floods, phytoplankton blooms, or nutrient-saturated combinations of total suspended solids and chlorophyll *a* in separate years will generally tend to align in the directions indicated in Figure IV-5. However, because of the high degree of seasonal and interannual variability in such data, these patterns might not be discernible at many stations, especially shallow locations where nutrient-saturated combinations of total suspended solids and chlorophyll *a* might be indistinguishable from phytoplankton blooms.

Generation of Management Options

A computer spreadsheet program for displaying data and calculating several options for achieving the water-column light requirements has been developed and has been made available in conjunction with this report through the Chesapeake Bay Program web site at www.chesapeakebay.net/tools. The spreadsheet program calculates median water quality concentrations, and evaluates them in relation to the minimum light requirements for growth to 0.5-, 1- and 2-meter restoration depths. Provisions are included for specifying a value for the water-column light requirement (WCLR) appropriate for mesohaline and polyhaline and regions (WCLR=0.22) or for tidal fresh and oligohaline areas (WCLR=0.13). When the observed median chlorophyll *a* and total suspended solids concentrations do not meet the water-column light requirement, up to four target chlorophyll *a* and total suspended solids concentrations that do meet the criteria are calculated based on four different management options (Figure IV-6). Under some conditions, some of the management options are not available because a 'negative' concentration would be calculated.

Option 1 is based on projection from existing median conditions to the origin (Figure IV-6A). This option calculates target chlorophyll *a* and total suspended solids concentrations as the intersection of the water-column light requirement line with a line connecting the existing median concentration with the origin, i.e., chlorophyll=0, TSS=0. Option 1 always results in positive concentrations of both chlorophyll *a* and total suspended solids.

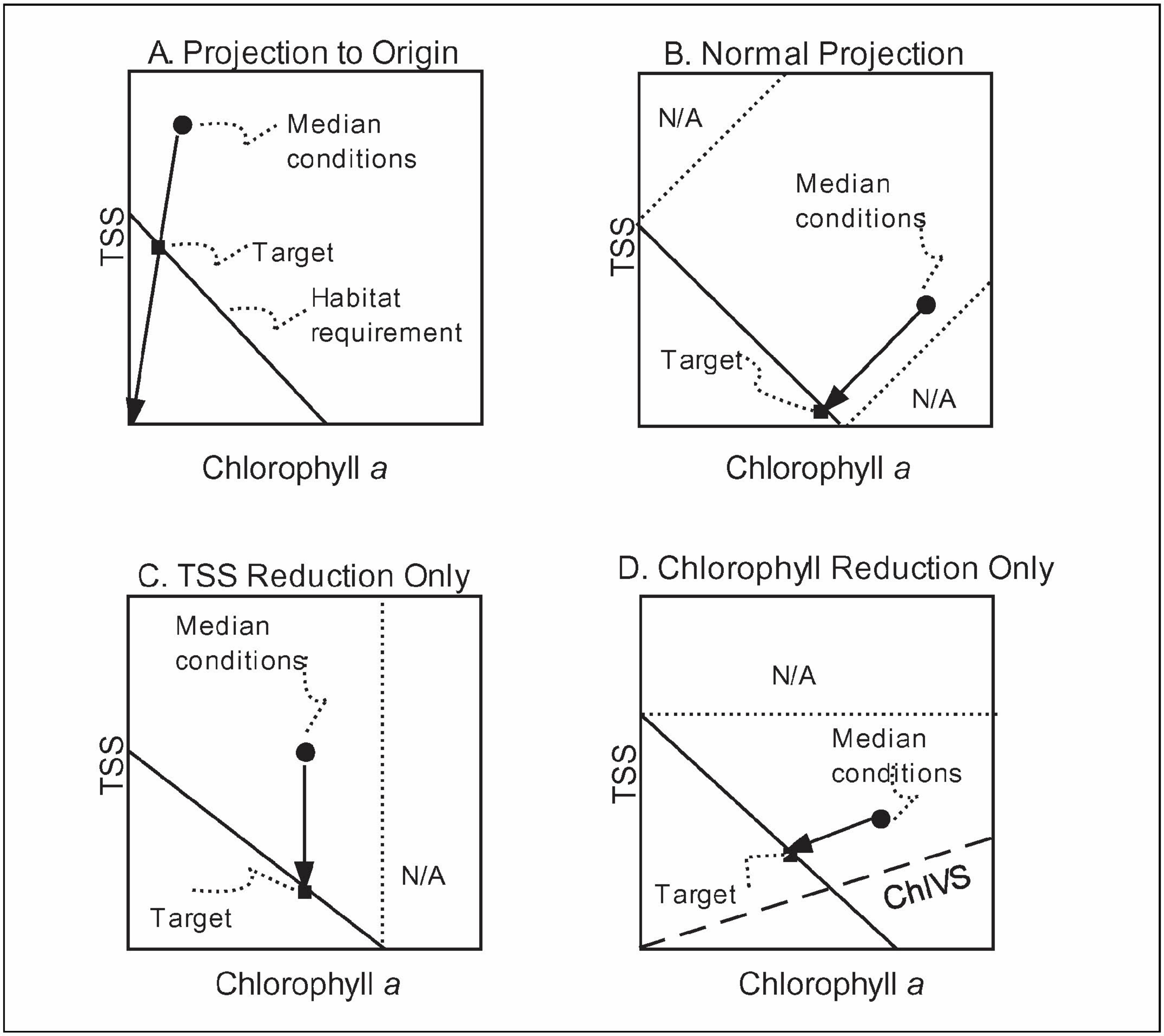

FIGURE IV-6. Illustration of Management Options for Determining Target Concentrations of Chlorophyll *a* and Total Suspended Solids. Illustration of the use of the diagnostic tool to calculate target growing-season median concentrations of total suspended solids (TSS) and chlorophyll *a* for restoration of SAV to a given depth. Target concentrations are calculated as the intersection of the water-column light requirement, with a line describing the reduction of median chlorophyll *a* and TSS concentrations calculated by one of four strategies: (A) projection to the origin (i.e. chlorophyll *a* =0, TSS=0); (B) normal projection, i.e. perpendicular to the water-column light requirement; (C) reduction in total suspended solids only; and (D) reduction in chlorophyll *a* only. A strategy is not available (N/A) whenever the projection would result in a 'negative concentration'. In (D), reduction in chlorophyll *a* also reduces TSS due to the dry weight of chlorophyll *a*, and therefore moves the median parallel to the line (long dashes) for ChlVS, which describes the minimum contribution of chlorophyll *a* to TSS.

Option 2 is based on normal projection (Figure IV-6B). It calculates target chlorophyll *a* and total suspended solids concentrations as the projection from existing median conditions perpendicular to the water-column light requirement. Geometrically, option 2 is the one that requires the least overall reductions in chlorophyll *a* and total suspended solids concentrations. In practice, target chlorophyll *a* and total suspended solids concentrations for the normal projection, when permissible (i.e., no negative concentrations are calculated), are frequently very similar to those calculated in option 1 using projection to the origin.

Option 3 is based on a total suspended solids reduction only (Figure IV-6C). This option calculates target chlorophyll *a* and total suspended solids concentrations assuming the target can be met by only reducing the concentration of total suspended solids. Option 3 is not available anytime the median chlorophyll *a* exceeds the TSS=0 intercept. Whenever a system is nutrient-saturated and light-limited, reduction of total suspended solids alone poses the risk of relieving light limitation and promoting further phytoplankton growth. Such a tendency is indicated on the diagnostic tool plot whenever data points tend to align parallel to the water-column light requirements lines as illustrated previously in Figure IV-5C (Wofsy 1983).

Option 4 is based on a chlorophyll *a* reduction only (Figure IV-6D). This option calculates target chlorophyll *a* and total suspended solids concentrations, assuming that the target can be met by only reducing the concentration of chlorophyll *a* (Figure IV-6D). Option 4 is not available whenever the median total suspended solids concentration exceeds the chlorophyll = 0 intercept of the water-column light requirement. The target total suspended solids concentration reported for option 4 is actually lower than the existing median, due to the suspended solids removed by reduction of phytoplankton and associated carbon, i.e., ChlVS.

SENSITIVITY OF TARGET CONCENTRATIONS TO PARAMETER VARIATIONS

The sensitivity of target concentrations calculated by each of the four management options was examined by calculating the change in target concentrations of chlorophyll *a* and total suspended solids in response to a 20 percent increase in each of the parameters (except Z_{max}) in Equation IV-5 that define the behavior of the diagnostic tool (Table IV-3). The diagnostic tool is formulated so that, in general, increases in parameter values result in decreases in target concentrations. An increase in the water-column light requirement increases the light required by SAV, resulting in lower target concentrations of total suspended solids and chlorophyll *a*. Increases in the specific-attenuation coefficients increase the light-attenuation coefficient, which reduces light availability at Z_{max}, and, therefore, also reduces the target water quality concentrations. Parameters in Equation IV-11 were an exception. Reduction in the ratios of particulate organic carbon:chlorophyll *a* and total volatile suspended solids:particulate organic carbon resulted in a negligibly higher target chlorophyll *a* concentration under option 1 (Table IV-3).

Reductions in target water quality concentrations were by far the most sensitive to increases in WCLR (Table IV-3). For management options 1 and 2, target chlorophyll *a* concentrations were reduced by about 27 percent from about 22 μg liter^{-1} to 16 μg liter^{-1}, and target total suspended solids by about 29 percent from nine mg liter^{-1} to 6.3 mg liter^{-1} with a 20 percent increase in WCLR (Table IV-3). Management options 3 and 4 were eliminated by a 20 percent increase in WCLR (Table IV-3). The large sensitivity to WCLR occurs because an increase in WCLR moves the entire line described by Equation IV-5 closer to the origin without changing the slope, i.e., in a manner similar to increases in Z_{max} (see Figure IV-5B).

The sensitivity of calculated target concentrations of chlorophyll *a* and total suspended solids to 20 percent increases in the remaining parameters in Equation IV-5 differed according to management option and parameter. Lowest target concentrations and greatest percentage reductions for chlorophyll *a* occurred in management option 4, i.e., chlorophyll *a* reduction only. The target concentration of chlorophyll *a* was, of course, insensitive to parameter variations under management option 3, total suspended solids reduction only. For management options 1 and 2, the calculated target chlorophyll *a* concentration was most sensitive to the parameter k_s, the specific-attenuation coefficient of total suspended solids, and relatively insensitive to increases in k_c, the specific-attenuation coefficient of chlorophyll *a*. Insensitivity to k_c may seem counterintuitive, because k_c governs the relative contribution of chlorophyll *a* to overall attenuation, and we might expect higher values to attribute more attenuation to chlorophyll *a*; but higher values of k_c also imply that a given reduction in chlorophyll *a* is more effective in reducing overall K_d, and hence less of a reduction is needed to achieve the target.

For total suspended solids, the lowest target concentrations and largest percentage reductions were calculated for option 3, total suspended solids reduction only (Table IV-3). Target total suspended solids concentrations were slightly sensitive to parameter variations under management option 4, due to the contribution of chlorophyll *a* to total suspended solids as expressed in Equation IV-11. For management options 1 and 2, the calculated target total suspended solids concentration was most sensitive to k_s. The higher sensitivity to k_s occurs because of the additional contribution of chlorophyll *a* to total suspended solids, so that increasing k_s has an effect similar to that of increasing the water-column light requirement.

SUMMARY AND CONCLUSIONS

The empirically observed exponential decay of light underwater, which can be characterized by a single attenuation coefficient, provides the means of deriving a simple expression for the percentage of surface light available to SAV at the bottom of a water column of any specified depth. The magnitude of the attenuation

TABLE IV-3. Percent change of the target chlorophyll *a* and total suspended solids concentrations calculated by the diagnostic tool in response to 20 percent increases in each of the parameters describing the dependence of diffuse attenuation coefficient on water quality (Equation IV-8). Baseline parameter values and the value after the 20 percent increase are given under the parameter name and units. Data used in the analysis were from the Maryland Chesapeake Bay Water Quality Monitoring Program for MWT5.1 station in Baltimore Harbor, restricted to the SAV growing season (April through October) 1986-1995. Baseline target concentrations are those calculated for the 1 m restoration depth minimum light requirement (Equation IV-9b) for each of the management options: 1-projection to origin; 2-normal projection; 3-total suspended solids reduction only; and 4-chlorophyll *a* reduction only (see text). N/A=not available.

Sensitivity of Management Option								
	Chorophyll *a*				Total Suspended Solids			
Parameter varied:	1	2	3	4	1	2	3	4
Baseline target	22.18	22.85	34.1	11.6	8.93	8.81	6.9	10.73
WCLR 0.22 to 0.264	-28.2	-25.8	N/A	N/A	-28.2	-29.2	N/A	N/A
k_c, (m^2 mg^{-1}) 0.016 to 0.0192	-5.6	-2.5	0.0	-10.1	-5.6	-7.4	-16.8	-1.5
k_s, (m^2 g^{-1}) 0.094 to 0.113	−12.4	−14.2	0.0	−56.0	−12.3	−11.4	−16.7	−7.2
K_{W+DOC}, (μ^{-1}) 0.32 to 0.384	-5.4	-4.9	0.0	12.9	-5.4	-5.6	-9.9	-2.8
POC:Chl (mg μg^{-1}) 0.04 to .048	0.0	−3.8	0.0	−14.9	−0.1	−1.9	0.0	−3.2
TVSS:POC 0.3 to 0.36	0.0	-3.8	0.0	-10.1	0.0	1.7	0.0	-8.0

coefficient is governed mainly by the concentrations of three water quality parameters: dissolved organic carbon, chlorophyll *a* and total suspended solids. Of these, only chlorophyll *a* and total suspended solids show substantial contribution to light attenuation at most locations around Chesapeake Bay. Sites where colored dissolved organic matter contributes substantially to attenuation, such as the Pocomoke River on the Maryland/Virginia border, are not considered in this analysis.

Linear partitioning of the diffuse-attenuation coefficient into contributions due to water plus dissolved organic carbon, phytoplankton chlorophyll *a* and total suspended solids involves known compromises in realism but is an approximation that has proved useful in the past and leads to a tractable solution for purposes of water quality management. Due to unexplained variability in the data from the Chesapeake Bay Water Quality Monitoring Program, specific-attenuation coefficients for water plus dissolved organic carbon, chlorophyll *a* and total suspended solids were estimated by a combined approach using statistical regression, optical modeling and comparison with literature values.

It will be shown elsewhere (Gallegos, unpublished) that the use of a single linear regression (Equation IV- 4), when applied across the full range of observed water quality conditions, produces biased diffuse-attenuation coefficients with respect to a more mechanistic model of light attenuation. Nevertheless, unbiased diffuse-attenuation coefficients can be obtained from a suitably calibrated optical water quality model. The present version of the diagnostic tool incorporates unbiased diffuse-attenuation coefficients determined by an optical model calibrated for a site near the mesohaline region of the mainstem Bay (Gallegos 1994). There is an urgent need for a regionally customized application of this approach (see "Directions for Future Research").

The diagnostic tool is based on a plot of measured concentrations of total suspended solids versus chlorophyll *a*, in relation to the linear combination of total suspended solids and chlorophyll *a* that meet the minimum light habitat requirement. Characteristic behaviors can be identified by the orientation of points: points scattered along the vertical (TSS) axis indicate attenuation dominated by episodic inputs of total suspended solids; points oriented parallel to the line defining the contribution of chlorophyll *a* to total suspended solids indicate variation of light attenuation governed by phytoplankton blooms; and points oriented parallel to the line describing the water-column light habitat requirement indicate that maximal chlorophyll concentrations are dependent on the concentration of total suspended solids, signifying a nutrient-saturated system.

An analysis of total suspended solids indicated that total volatile suspended solids were a variable fraction of total suspended solids, and that on average, particulate organic carbon is about 30 percent of total volatile suspended solids. Using a reasonable estimate of the phytoplankton carbon:chlorophyll *a* ratio, along with the contribution of particulate organic carbon to total volatile suspended solids, indicated that phytoplankton carbon contributes to the overall total suspended solids. Any reduction in chlorophyll *a* would be accompanied by a proportionate decrease in total suspended solids.

Up to four management options for moving the system to conditions that meet specified water-column light requirements are calculated by the diagnostic tool. The precision of the calculations obviously implies a degree of control over water quality conditions that clearly is not always attainable. Nevertheless, reporting of four potential targets provides managers with an overall view of the magnitude of the necessary reductions, and some of the tradeoffs that are available. Furthermore, the spreadsheet reports the frequency with which the water-column light requirements for each restoration depth are violated by the individual measurements. This information may be useful in the future if water-column light requirements for SAV growth and survival become better understood in terms of tolerance of short-term light reductions.

Directions for Future Research

Continued collection of monitoring data is necessary to track recovery (or further degradation) of the system with respect to the optical water quality targets defined for the various regions using the diagnostic tool. However, it is doubtful that additional monitoring data will improve the ability to derive statistical estimates of specific-attenuation coefficients by regression analysis. Inherent variability in the spectral absorption and scattering properties of the optical water quality parameters, combined with normal uncertainty associated with sampling and laboratory analyses, probably account for the low coefficients of determination and statistically insignificant estimates of some specific-attenuation coefficients.

Nevertheless, some attempt to determine regionally based estimates of optical properties should be made, because of the pronounced changes in the nature of particulate material that occur from the headwaters to the mouth of major tributaries as well as the mainstem Chesapeake Bay itself. An approach based on direct measurement of particulate absorption spectra and optical modeling will be needed to obtain regionally customized diagnostic tools.

CHAPTER V

Epiphyte Contributions to Light Attenuation at the Leaf Surface

Building from the diagnosis and quantification of water-column contributions to attenuation of light, the present chapter focuses specifically on how changes in water quality variables alter the light available at SAV leaves and considers effects of light attenuation resulting from substances both in the overlying water column (phytoplankton, suspended particles and dissolved organics) and attached to SAV leaves (epiphytic algae, organic detritus and inorganic particles). A simple model is developed to calculate photosynthetically available radiation (PAR) at the leaf surface for plants growing at a given restoration depth (Z) under specific water quality conditions. The computed value for PAR at the plant leaves is compared to a target "minimum light requirement" for SAV survival, which is defined in Chapter VII of this report.

The overall objective is to apply this model using water quality monitoring data to estimate growing season mean light levels at SAV leaves for a particular site or geographic region. The calculated light levels at SAV leaves are then compared to the applicable minimum light requirement value to assess whether water quality conditions are suitable to support survival and growth of SAV. The relative contributions of water column vs. epiphytic substances in attenuating incident light to SAV leaves are also computed. The scientific basis of this model is described here in some detail.

Numerous models have been developed previously for making theoretical computations of SAV growth considering light attenuation by water-column materials only (e.g., Best 1982; Zimmerman *et al.* 1987) or water-column plus epiphytic substances (Wetzel and Neckles 1986; Hootsman 1991; Bach 1993; Kemp *et al.* 1995; Madden and Kemp 1996; Fong *et al.* 1997). Other studies have described simple statistical models for predicting depth distribution of SAV in relation to variations in observed data on water column transparency (e.g., Rørslett 1987; De Jong and De Jong 1992; Scheffer *et al.* 1993). The model described in this chapter combines these approaches to calculate, from field observations, light available for SAV survival and growth, considering light attenuation from both water column and epiphytic materials.

APPROACH AND METHODOLOGY

To compute median PAR at the leaf surface of SAV, the model requires SAV growing season medians for four water quality variables: 1) dissolved inorganic nitrogen (nitrate + nitrite + ammonia), or DIN; 2) dissolved inorganic phosphorus (primarily phosphate), or DIP; 3) total suspended solids (TSS); and 4) diffuse downwelling PAR attenuation coefficient (K_d). Values for K_d are either obtained from direct measurements of PAR decrease with water depth using a cosine-corrected sensor, or they are calculated from observations on the depth at which a Secchi disk disappears (see Chapter III for the Secchi depth/K_d conversion). An implicit assumption in this analysis is that light (PAR) availability is the primary environmental factor that limits SAV survival and growth in temperate coastal waters (Duarte 1991a; Dennison *et al.* 1993; Zimmerman *et al.* 1995). In the model, light is attenuated by dissolved and particulate materials in the water column (Chapter IV) and by biotic and abiotic epiphytic materials accumulated on SAV leaves.

The light attenuation to the SAV leaf surface is calculated using an exponential equation, with a depth-dependent term for water column shading and a mass-specific term for epiphyte attenuation. These are standard equations widely used in aquatic science (Kirk 1994) and ecosystem modeling (e.g., Hootsman 1991; Madden and Kemp 1996). The depth of the site is defined by the local bathymetry and the "target depth" for SAV restoration. Specific targets and formally adopted goals for restoration of SAV in Chesapeake Bay, originally defined and quantified in Batiuk *et al.* (1992) and Dennison *et al.* (1993), are summarized in Chapter VIII.

Specifically, the model calculates PAR at the SAV leaf surface for a given water depth (I_{zs}) as a fraction of the incident radiation at the water surface (I_o) using the following formulation:

$$[I_{zs}/I_o] = [e^{-(K_d)(Z)}][e^{-(K_e)(B_e)}] \qquad \text{(V-1)}.$$

There are four variables on the right side of this equation: 1) the water-column PAR attenuation coefficient, K_d ; 2) the depth of leaves growing up from sediments at the lower edge of a potential SAV habitat, Z; 3) the biomass of epiphytic algae growing on SAV leaves, B_e; and 4) the biomass-specific PAR attenuation coefficient for epiphytic algal material, K_e.

The model user defines Z with the assumption that SAV must grow upward from the sediment surface early in the growing season. As the plants grow upward and shoots get closer to the water surface, they begin to self-shade, which is not considered directly in this analysis. K_d is an input variable derived from field monitoring data. The model computes B_e from input water quality monitoring data on dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d and the selected value for Z. The fourth variable, K_e, is estimated from two statistical correlations derived from experimental data (Staver 1984) and field observations in oligohaline and mesohaline regions of the Potomac and Patuxent River estuaries (Carter *et al.*, unpublished data; Boynton *et al.*, unpublished data) and in the mesohaline and polyhaline reaches of the York River estuary (Neckles 1990). The first correlation is between K_e and the ratio B_e/B_{de}, where B_{de} is the total dry weight of epiphytic material (both algal and other material per dry weight of SAV leaf). The ratio, B_e/B_{de}, is itself calculated from a second statistical relationship with total suspended solids, using total suspended solids water quality monitoring data as input to the computation.

MODEL DESCRIPTION

In this section, each step in the model calculation is explained and its derivation described (Table V-1). All key assumptions are stated explicitly, and their implications are discussed. The model is based on the relation described in Equation V-1, where light (as a fraction of that at the water surface) is attenuated by two exponential relations. One of these relations $[e^{-(K_d)(Z)}]$ accounts for attenuation by the water overlying SAV leaves and dissolved and suspended materials contained in that water, and the other term $[e^{-(K_e)(B_e)}]$ accounts for effects of materials accumulated on SAV leaves.

Most of the model description that follows explains how the second of these terms was derived from a combination of statistical relations and numerical model simulations. First, a description is provided on how an estimate of potential biomass of epiphytic algae is calculated from nutrient concentrations and other water quality measurements. Next, an approach is described for estimating a biomass-specific PAR attenuation coefficient for epiphytic material (K_e) in relation to the ratio of epiphytic algal biomass (B_e, as chlorophyll *a*) to total dry weight of material (B_{de}) on SAV leaves. Then a statistical correlation is described for estimating the ratio (B_e/B_{de}) in relation to water quality conditions.

Computing Epiphytic Algal Biomass (B_e) from Nutrient Concentration

A numerical ecosystem simulation computation is used in the first three steps of the overall model to compute growth of epiphytic algal biomass as a function of nutrient concentrations (e.g., Twilley *et al.* 1985; Borum 1985) and light availability (e.g., Short *et al.* 1995; Moore *et al.* 1996). This numerical submodel (adapted from Kemp *et al.* 1995 and Madden and Kemp 1996) is used to calculate mean epiphytic algal biomass from input data on dissolved inorganic nutrient concentrations, water depth and K_d. The numerical model also takes into account other environmental factors including temperature (Madden and Kemp 1996), grazing on epiphyte biomass (Hootsman and Vermaat 1985; Jernakoff *et al.* 1996) and water

TABLE V-1. Summary of the approach used to estimate photosynthetically available radiation at the leaf surface of submerged aquatic vegetation using water quality data routinely monitored in Chesapeake Bay.

Step in Model Calculation *Functional Relationship*	**Input Data**	**Source of Model Relationship**	**Units**
1) Decide limiting nutrient DIN/DIP > 16 , use DIP DIN/DIP £ 16 , use DIN	DIN, DIP	Fisher et al. 1992	μM
2) Derive general equation to calculate epiphyte biomass $B_e = (B_e)_m\ [1 + 208\ (DIN^{-K_{N(OD)}})]^{-1}$ • $(B_e)_m$ = maximum B_e value • $K_{N(OD)}$ = characteristic coeff.	DIN, DIP	Numerical model (Madden and Kemp 1996)	B_e , $gCgC^{-1}$ DIN, μM $K_{N(OD)}$, none
3) Calculate PAR effect on $K_{N(OD)}$ and $(B_e)_m$ $(B_e)_m = 2.2 - [0.251\ (OD^{1.23})]$ • OD = Optical Depth = K_d (Z) $K_{N(OD)} = 2.32\ (1 - 0.031\ OD^{1.42})$	K_d, Z	Numerical model (Madden and Kemp 1996)	K_d, m^{-1} Z, m
4) Calculate epiphyte dry weight $B_{de} = 0.107\ TSS + 0.832\ B_e$	TSS B_e	Regression from experimental data (e.g., Staver 1984)	TSS, mg l^{-1} B_e , mg chl gdw^{-1} B_{de} , gdw gdw^{-1}
5) Calculate epiphyte biomass-specific PAR attenuation coeff. $K_e = 0.07 + 0.32\ (B_e / B_{de})^{-0.88}$	B_e , B_{de}	Regression from experimental and field data	B_e , μg chl cm^{-2} B_{de} , mg dw cm^{-2} K_e , $cm^2 \mu g\ chl^{-1}$
6) Calculate PAR at SAV leaves (I_{ze}) I_{ze} / I_o = Install Equation Editor and double-click here to view equation.	DIN, DIP, K_d, TSS, Z	Combining steps #1-5 (from above)	DIN, μM DIP, μM TSS, mg l^{-1} K_d, m^{-1}
7) Compare SAV leaf PAR with Minimum Light Requirement	I_{ze} / I_o	See Chapter VII	%

exchange rate (Sturgis and Murray 1997). Earlier versions of this numerical model were calibrated using data from field sites in Chesapeake Bay (Kemp *et al.* 1995; Madden and Kemp 1996). The numerical model used in this analysis was calibrated using data from both field sites (e.g., Lubbers *et al.* 1990) and controlled mesocosm experiments (Sturgis and Murray 1997).

The molar ratio of concentrations (SAV growing season mean values) of dissolved inorganic nitrogen to dissolved inorganic phosphorus (DIN:DIP) is compared to the Redfield ratio of 16:1 (Redfield 1934) to select which nutrient should be used in the analysis (Table V-1). Here, a single limiting nutrient is assumed. If the molar ratio is ≤ 16, dissolved inorganic nitrogen data are used; if the ratio is >16, dissolved inorganic phosphorus data are used. This assumption is generally consistent with observations from Chesapeake Bay algal bioassay and mesocosm experiments (D'Elia *et al.* 1986; Neundorfer and Kemp 1993; Fisher *et al.* 1992, 1998).

The numerical ecosystem simulation was used to compute a family of sigmoidal shaped curves relating nutrient concentration to epiphyte biomass, with different curves for different water column light regimes (Figure V-1). Model biomasses are calculated in terms of organic carbon, so epiphytes are reported here as g C epiphyte g C SAV^{-1} (Table V-1). Light regimes are characterized by the "optical depth," which is the product of K_d times the water depth Z (e.g., Kirk 1994). It can be seen that changes in optical depth have a more pronounced effect on the maximum epiphyte biomass attained than on nutrient responses at low dissolved inorganic nitrogen concentrations. Consistent patterns are evident in the family of curves generated by this model, and these can be described by the following general function:

$$B_e = (B_e)_m\,[1 + 208(\mathrm{DIN}^{-K_{N(OD)}})]^{-1} \qquad \text{(V-2)}$$

where the two rate coefficients $(B_e)_m$ and $K_{N(OD)}$ are the maximum possible epiphytic algal biomass (ultimately limited by space) and a shape coefficient describing the B_e vs. dissolved inorganic nitrogen (DIN) relationship, respectively. As the optical depth (OD = $Z \bullet K_d$) increases, values for $(B_e)_m$ decrease, while values for $K_{N(OD)}$ increase.

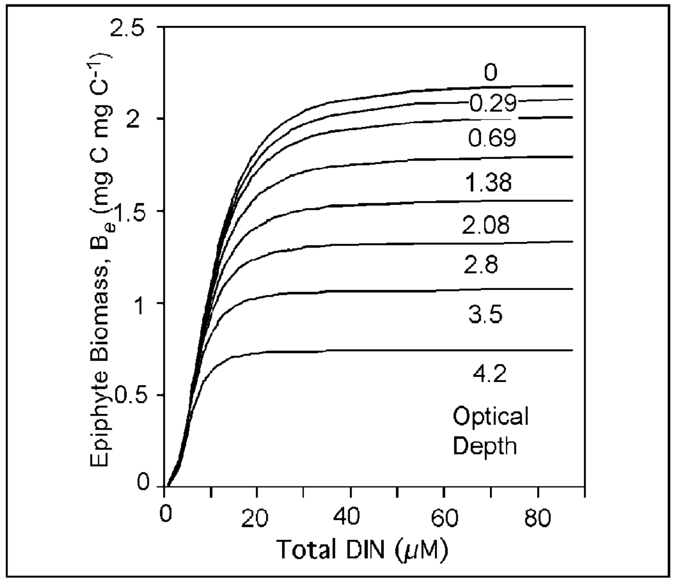

FIGURE V-1. Epiphytic Algal Biomass Responses to Varying DIN and Light Conditions. Calculated responses of epiphytic algal biomass (B_e, mg C/mg C SAV) to changes in dissolved inorganic nitrogen (DIN) concentration under varying light conditions in estuarine waters of Chesapeake Bay. Each curve represents estimated response under specific light regimes, characterized by different optical depths (OD = $K_d \bullet Z$). Relationships were generated from numerical ecosystem simulation model (modified from Madden and Kemp 1996) assuming constant biomass of host SAV plant over growing season (May-August). Similar functions are predicted for B_e versus dissolved inorganic phosphorus (DIP) concentrations, with DIP = DIN/16.

Statistically significant relationships were fit between model-generated values for the coefficient $(B_e)_m$ and input values for optical depth

$$(B_e)_m = 2.2 - [0.251\,(OD^{1.23})] \qquad \text{(V-3)}$$

and between the coefficient $K_{N(OD)}$ and optical depth,

$$K_{N(OD)} = 2.32\,(1 - 0.031\,OD^{1.42}) \qquad \text{(V-4).}$$

The relationships described in equations V-3 and V-4 (Figure V-2) can then be substituted back into Equation V-2 to produce a single continuous function relating epiphyte biomass (B_e) to two input variables, dissolved inorganic nitrogen (or dissolved inorganic phosphorus) and OD. Although Equation V-4 predicts that $K_{N(OD)}$ 0 at OD 11.55, neither epiphytes nor SAV are capable of growing at such high values of OD.

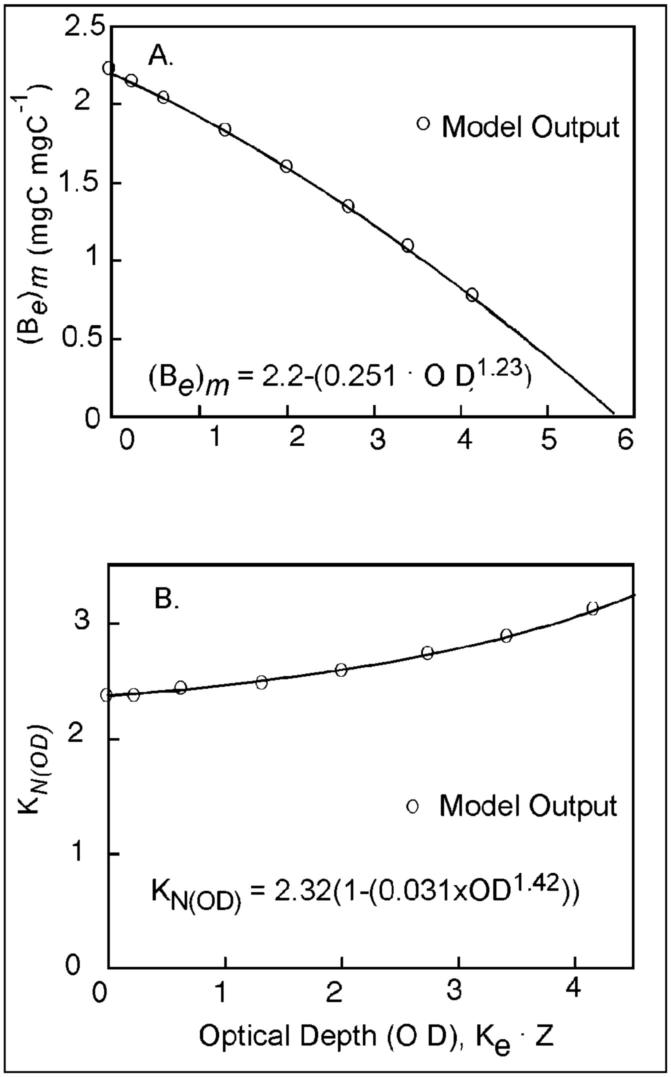

FIGURE V-2. Model Predicted Responses of Epiphytic Algal Biomass to Changes in Optical Depth and DIN Concentrations. Model predicted the effects of changing optical depth (OD = K_d • Z) on coefficients describing response of epiphytic algal biomass B_e to changes in dissolved inorganic nitrogen (DIN) concentrations (see Fig. V-1). The coefficient $(B_e)_m$ is the maximum possible value for B_e at a given OD (upper panel, A), and $K_{N(OD)}$ is a coefficient describing the shape of the B_e versus DIN relationship (lower panel, B).

There are a limited number of complete data sets available for testing these relations between nutrient concentration, light availability and epiphyte biomass. This is, in part, because of the difficulty in obtaining nutrient data integrated over appropriate time scales to coincide with epiphytic algal growth (e.g., Sand-Jensen and Borum 1991; Duarte 1995). Data used as inputs to equations V-2 through V-4 to calculate epiphyte biomass were measurements of dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d and Z (averaged over the course of the studies) from two field sites in Chesapeake Bay tidal tributaries—the Potomac River Estuary (Carter *et al.*, unpublished data) and the Patuxent River Estuary (Boynton *et al.*, unpublished data)—and from a recent mesocosm experiment (Sturgis and Murray 1997).

Epiphyte biomass measurements are based on artificial substrates deployed and retrieved in the two referenced field studies and on direct measurements from leaves of *Potamogeton perfoliatus* in the referenced mesocosm experiments. All biomass measurements were converted from chlorophyll *a* to carbon units using measured chlorophyll *a*:carbon ratios. The model assumed a constant (mean) value for SAV biomass over the course of a 60-day simulation. Although there were only eight separate data points for this comparison, the "predicted" (PRED) biomass values compared well to measured (OBS) values (Figure V-3). There appears to be a slight bias, where the prediction tends to underestimate measured values at moderate biomasses; however, the relationship is statistically significant (OBS = 0.21 + 0.93 PRED, $r^2 = 0.81$).

Relationships between epiphytic algal biomass and nutrient concentrations or loading rates previously have been reported for a wide range of conditions. While most of these are from experimental manipulations (Philips *et al.* 1978; Twilley *et al.* 1985; Neundorfer and Kemp 1993; Neckles *et al.* 1993; Williams and Ruckelshaus 1993; Short *et al.* 1995; Sturgis and Murray 1997), several field studies also revealed positive relations between nutrients and epiphytic algal biomass (Borum 1985; Cattaneo 1987; Lapointe *et al.* 1994). Many recent studies have emphasized the importance of invertebrate grazing as a control on epiphytic algal biomass (e.g., Cattaneo 1983; Orth and van Montfrans 1984; Hootsman and Vermaat 1985; Howard and Short 1986), and other studies suggest that heavy grazing pressure may preclude epiphytic algal responses to nutrients (Neckles *et al.* 1993; Jernakoff *et al.* 1996; Alcoverro *et al.* 1997). Results of other recent studies have indicated that muted epiphytic algal responses to nutrient enrichment may also result from shading associated with phytoplankton growth (e.g., Taylor *et al.* 1995; Short *et al.* 1995; Lin *et al.* 1996) or other sources of turbidity (Moore *et al.*

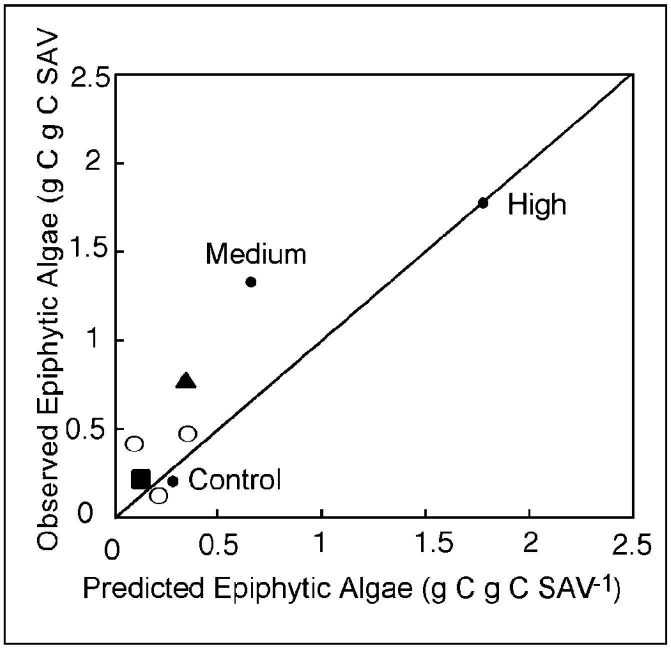

FIGURE V-3. Observed vs. Predicted Epiphytic Algal Biomass. Comparison of observed epiphytic algal biomass and predicted values (from Equation V-2 and Figure V-1) using inputs of data for dissolved inorganic nitrogen (or dissolved inorganic phosphorus) and optical depth (OD = K_d • Z). Data and model predictions were averaged over duration of field deployments of artificial substrates (2 weeks) or mesocosm experiments (6 weeks), and data are averaged over multiple sites and replicate mesocosms. Values for B_e were from four sources: 1) *Potamogeton perfoliatus* plants in mesocosm studies (closed circles, Sturgis and Murray 1997); 2) artificial substrates from field studies in the Potomac River estuary (triangles, Carter *et al.*, unpublished); 3) artificial substrates from field studies in the Patuxent River estuary (squares, Boynton *et al.*, unpublished); and 4) artificial substrates from field studies in the York River estuary (open circles, Neckles 1990). High, Medium, and Control refer to nutrient treatments in mesocosm studies.

1996). Shear stress associated with waves can also reduce the accumulation of epiphytes on SAV leaves, with open exposure to waves leading to reduced accumulation of epiphytes (Strand and Weisner 1996; Kendrick and Burt 1997). Finally, there is growing evidence that epiphyte responses to nutrient enrichment may vary with the residence time of water flushing SAV beds (Kemp *et al.* 1983; Sturgis and Murray 1997; Murray *et al.* unpublished), as regulated by physiographic characteristics of the site (Kemp *et al.* 1983) and by SAV abundance (Ward *et al.* 1984; Rybicki *et al.* 1997).

The structure of the numerical ecosystem simulation model used in this study allows for sensitivity analyses of how light, grazing and flushing rate might alter the relationship between nutrient concentration and biomass of epiphytic algae. Effects of light availability in concert with water depth were discussed previously, and model simulation results (Figure V-2) illustrate that epiphytic algal growth will be relatively unaffected by nutrient enrichment in low light environments (e.g., the bottom curve in Figure V-1 at OD = 4.2). Light effects are already directly captured in the present version of the Figure V-1 model algorithm described here. Both grazing rates on epiphytes and in water exchange rates are fixed at baywide average values in the present version of this algorithm. Potential effects of these two factors on the calculated nutrient-epiphyte relationship can be investigated using numerical model simulations.

Model simulations revealed that high grazer biomass (e.g., 1 g C m^{-2}) can completely mask the relationship between epiphytic algal biomass and dissolved inorganic nitrogen (Figure V-4, upper panel). By contrast, at lower grazer biomass (0.2 g C m^{-2}), epiphytic algae accumulate sharply with increasing dissolved inorganic nitrogen concentrations, reaching biomass levels that exceed two grams C (g C SAV)$^{-1}$ at 30 μM dissolved inorganic nitrogen (Figure V-4, upper panel). The model suggests that the dissolved inorganic nitrogen-epiphyte relationship is highly sensitive to grazing effects at herbivore biomass levels between 0.8 and 1.0 g C m^{-2} (assuming a mean grazer size of 1 mg dw).

Field data on herbivorous epifaunal abundances are available from the early 1980s for one *Z. marina* site in the lower Chesapeake Bay (Fredette *et al.* 1990) and for two sites (dominated by *Potamogeton spp.* and *Ruppia maritima*) in the mesohaline Chesapeake Bay (Lubbers *et al.* 1990). Using these data, along with reported allometric relations between epifaunal size and consumption (Cattaneo and Mousseau 1995), potential grazing rates on epiphytes in these SAV beds were estimated. At the *Z. marina* site, calculated grazing rates appear to have been capable of controlling epiphyte growth, while moderate-to-low grazing rates at the mesohaline Bay sites would have been incapable of regulating epiphyte biomass. This is consistent with observed trends in SAV abundance at these two Chesapeake Bay sites in recent decades, where SAV populations have declined more in the mesohaline than in the polyhaline regions of the estuary. More

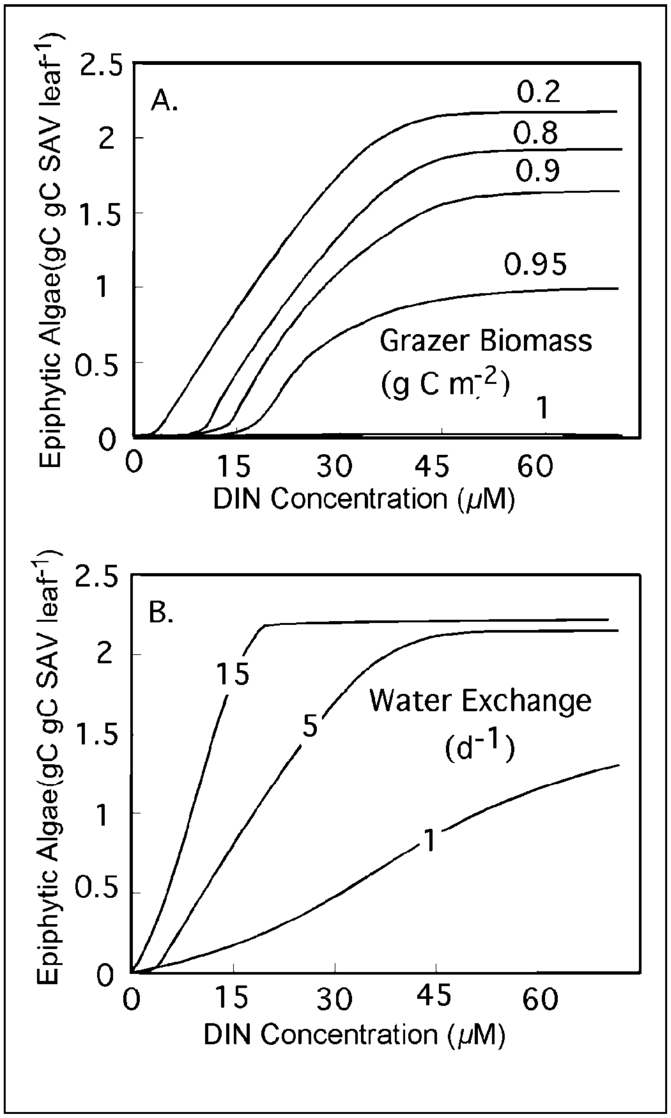

FIGURE V-4. Modeled DIN vs. Epiphytic Algal Biomass Responses Under Varying Grazer Biomass and Water Exchange Rates. Model calculated changes in the relationship of dissolved inorganic nitrogen (DIN) versus epiphytic algal biomass in response to variations in biomass of herbivorous epiphyte grazers (upper panel, A) and rates of water exchange with adjacent environments (lower panel, B).

recent mesocosm experiments, where epifaunal grazing rates were comparable to those at this eelgrass site in the 1980s, revealed that grazing effectively precluded epiphyte response to nutrient enrichment (Neckles *et al.* 1993), further demonstrating the ability of these model calculations to simulate the impact of grazing.

The present model also suggests strong effects of water exchange rate on epiphyte responses to nutrient enrichment. The initial slope of the relationship between epiphyte biomass and dissolved inorganic nitrogen concentration declines with water exchange rate (Figure V-4, lower panel). While exchange rate has little influence on this relationship at high nutrient levels, the effect is substantial at concentrations below 30 μM. This relationship arises primarily because at low flushing rates, the relatively high initial (spring) biomass of SAV compared to epiphytes confers a competitive advantage to the plants. In addition, biomass-specific nutrient uptake rates tend to saturate at much higher concentrations for SAV leaf uptake compared to uptake by epiphytic algae (e.g., Day *et al.*, 1989). Thus, at low water exchange rates, the rapid uptake and storage of nutrients by macrophytes is sufficient to lower local (at the plant leaves) nutrient concentrations substantially, and consequently epiphyte growth. Under these conditions of relatively high SAV biomass and slow water exchange, nutrient concentrations tend to be much lower inside than outside the bed. At higher flushing rates, the ability of plants to regulate local nutrient concentrations is swamped by rapid water exchange, such that there is little gradient in nutrient concentrations from outside to inside the SAV bed. Limited available field data support the idea that nutrient concentration gradients can be maintained by plant uptake under conditions of high SAV biomass and rapid growth, coupled with relatively slow water exchange rates (e.g., Bulthuis *et al.* 1984; Moore 1996).

In summary, these sensitivity analyses (Figure V-4) illustrate that the present numerical model is relatively robust in its ability to simulate the effects of a wide range of environmental factors on nutrient-epiphyte relationships. It is also evident that refined application of this model analysis to specific field sites must be attentive to the nutrient-epiphyte relationship that may be affected by other factors such as grazing and flushing rates. There is a pressing need for field data on these factors to better calibrate these effects.

Epiphyte Biomass-Specific PAR Attenuation Coefficient

An extensive review of the published literature and unpublished reports was conducted to compile data on direct measurements of light attenuation attributable to epiphytic material on SAV leaves. A limited number of studies were identified with direct estimates of epiphytic algal biomass-specific PAR attenuation coefficient, K_e (cm^2 μg $chla^{-1}$). These studies were associated with various SAV species, including *Potamogeton perfoliatus* (Staver 1984; Twilley *et al.* 1985; Neundorfer and Kemp 1993), *P. pectinatus* (Vermaat and Hootsman 1994; van Dijk 1993), *R. maritima* (Twilley *et al.* 1985), *Z. marina* (Sand-Jensen and Borum 1983; Neundorfer and Kemp 1993; Neckles *et al.*, unpublished), *Heterozostera tasmanica* (Bulthuis and Woelkerling 1983a), *Posidonia australis* (Silberstein *et al.* 1986) and *Thalassia testudinum* (Kemp *et al.* 1989; Dixon and Leverone 1995).

Unfortunately, these studies used four different conventions for units of measure of epiphyte abundance: 1) μg chlorophyll *a* cm^{-2} (leaf); 2) mg dry weight cm^{-2} (leaf); 3) mg ash-free dry weight cm^{-2} (leaf); 4) g dry weight epiphyte per g dry weight (SAV leaves). Information on plant morphology was used to convert between leaf area and dry weight (e.g., Duarte 1991b), and observed carbon:chlorophyll *a* ratios (e.g., Staver 1984) were used to convert between μg chlorophyll *a* and mg ash-free dry weight for epiphytic material.

Although it was anticipated that values of attenuation coefficients would converge from the different sources, this was not the case. Estimates of K_e varied as much as two- to threefold, expressed either in terms of epiphytic algal chlorophyll *a* or total dry weight of epiphytic material.

One factor contributing to the widely varying estimates of K_e appears to be the composition of epiphytic material in terms of relative contributions of algal biomass, detritus and inorganic particles. Although the ratio of epiphytic algal biomass to detrital epiphytic matter may vary somewhat over the course of a growing season (Staver 1984), it was assumed that epiphytic algal biomass would serve as an index of contributions of both living and non-living organic matter to total K_e. However, because of the highly dynamic nature of resuspension and deposition (e.g., Ward *et al.* 1984), it was assumed that the contribution of inorganic solids to K_e could vary widely from site to site, depending on hydrographic and sedimentological conditions. Presumably, these inorganic materials are resuspended from bottom sediments, transported into SAV beds and deposited onto SAV leaves, where they may be incorporated into the epiphytic matrix (e.g., Brown and Austin 1973; Ward *et al.* 1984; Kendrick and Burt 1997).

In an experimental study, Staver (1984) considered how K_e varied with the ratio of epiphyte biomass (B_e, mg chlorophyll *a* cm^{-2} substrate) to total dry weight (B_{de}, g dw cm^{-2} substrate). Here, nearly 100 simultaneous observations of K_e, B_e, and B_{de} were separated into four groups based on this ratio (B_e: B_{de}). While Staver (1984) found great variance when all observations were pooled, highly significant correlations between B_e and PAR attenuation (the slope of which is K_e) were observed when the data were separated (according to the ratio of biomass to dry weight) into the four groups.

Recent field studies in two tidal tributaries of Chesapeake Bay—the Potomac River estuary (Carter *et al.* unpublished) and the Patuxent River estuary (Boynton *et al.* unpublished)—have provided an expanded data base. These field data were combined with the previously described mesocosm data (Staver 1984) to generate a significant inverse relationship between K_e and B_e:B_{de} (Figure V-5),

$$K_e = 0.07 + 0.322\,(B_e / B_{de})^{-0.88} \qquad \text{(V-5).}$$

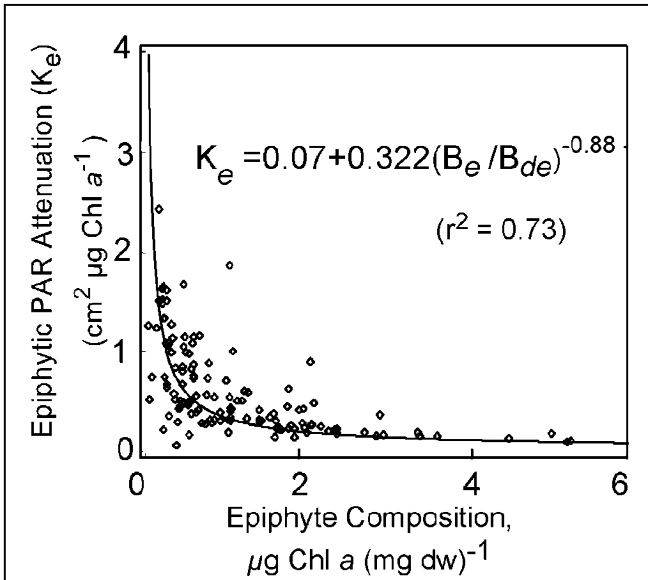

FIGURE V-5. Epiphytic Composition vs. Epiphytic PAR Attenuation. Relationship between the composition of epiphytic material (μg chlorophyll-*a* (mg dry weight)$^{-1}$) and the biomass-specific PAR (photosynthetically available radiation) attenuation coefficient (cm^2 μg chl-a^{-1}) for epiphytes. Data are pooled from a pond mesocosm experiment (Staver 1984) and from field studies in Patuxent River estuary (Boynton *et al.*, unpublished) and Potomac River estuary (Carter *et al.*, unpublished). In all cases, epiphytic material was measured on artificial substrates.

Equation V-5 expresses a complex relationship in that its slope is essentially a ratio of ratios. However, it clearly indicates that the chlorophyll *a*-specific attenuation coefficient, K_e, increases (in a non-linear way) as the relative contribution of chlorophyll *a*-bearing material decreases. Since light attenuation is measured per unit algal chlorophyll *a*, the increase in K_e with decreasing values of B_e: B_{de} (mg chl-*a* g dry wt^{-1}) is due to the light-attenuating effects of non-algal materials. Thus, while K_e appears to vary widely among sites depending on physical conditions, it can be predicted with confidence from data on the ratio of epiphyte biomass to dry weight.

Similar hyperbolic relationships can be produced for each of the three separate field and mesocosm data sets. There was no statistically significant difference among any of these, nor between any particular site and the relationship illustrated in Figure V-5 for the pooled data. At low values of the epiphyte composition ratio, B_e: B_{de} < 0.5 mg chl-*a* g dry wt^{-1}, Equation V-5 is highly sensitive to small changes in that ratio. However, applying field data on B_e: B_{de} to Equation V-5 illustrated that calculated values of K_e rarely exceeded 1.5 cm^2 μg chl a^{-1}.

The option of calculating the biomass-specific epiphyte attenuation coefficient (K_e) in terms of total dry weight of epiphytic material rather than algal chlorophyll *a* was also explored. The dry weight-specific coefficient yielded a significant, but slightly weaker, relationship compared to that for chlorophyll *a*-specific attenuation. Therefore, the chlorophyll *a*-specific attenuation coefficient was retained in the model because chlorophyll *a* is a better measure of algal biomass, which is what is being predicted in Equation V-2.

Estimating the Ratio of Epiphyte Biomass to Total Dry Weight

The next step of the analysis involves deriving a means for computing, from available water quality monitoring parameters, the ratio of epiphytic algal biomass to total dry weight of epiphytic materials. Toward this end, it was postulated that the contribution of inorganic particles to total dry weight of epiphytic material would increase with sediment resuspension and associated water-column concentrations of total suspended solids.

Previous studies in Chesapeake Bay have shown that rates of total suspended solids deposition in SAV beds are proportional to SAV biomass and to total suspended solids load (Ward *et al.* 1984). It was further assumed that sedimenting particles would tend to be trapped in the organic matrix of epiphytic material in proportion to the biomass of algal epiphytes. In hydrodynamically active coastal environments, where SAV plants are in constant motion, very little of the sinking particles would adhere to leaves without the organic 'glue' associated with algal biomass. In fact, in a Swedish lake, the total dry weight of epiphytic materials (B_{de}) was inversely related to wave exposure (Strand and Weisner 1996).

While there is no published quantitative description of the relationship between total suspended solids, B_e and B_{de}, the assumed pattern is consistent with numerous observations with SAV in field and experimental conditions (e.g., Kemp *et al.* 1983; Twilley *et al.* 1985). An existing data set was used to develop an empirical relationship to calculate B_{de} [(g dw epiphytic material) (g dw SAV)$^{-1}$] from data on B_e [(mg epiphyte chl-*a*) (g dw SAV)$^{-1}$] and concentrations of total suspended solids (mg l^{-1}]) in the adjacent water. This relationship would allow values for a biomass-specific epiphytic PAR attenuation coefficient (K_e) to be estimated from the previous step in the analysis.

Simultaneous measurements of total suspended solids, B_{de} and B_e were available from a set of studies in experimental ponds (Twilley *et al.* 1985; Staver 1984). A significant (r^2 = 0.85) relationship was observed using the data,

$$B_{de} = 0.107\ TSS + 0.832\ B_e \qquad \text{(V-6).}$$

To test the robustness of Equation V-6, values for dry weight of epiphytic material (B_{de}) predicted from the equation were compared with measured values. A highly significant fit was observed between model and data (r^2 = 0.85, Figure V-6), although predicted values tend to underestimate observed values at intermediate values of B_{de} (2-4 mg dw mg dw^{-1}). An alternative non-linear formulation with an interactive term ($TSS \cdot B_e$) on the right side of the equation provided a substantially poorer statistical fit.

Field data with simultaneous measurements of total suspended solids, B_{de} and B_e were much harder to identify. Attempts were made to use data collected in the Potomac and Patuxent River estuaries, where observations were made on one- to three-week intervals; however, these data yielded substantially weaker

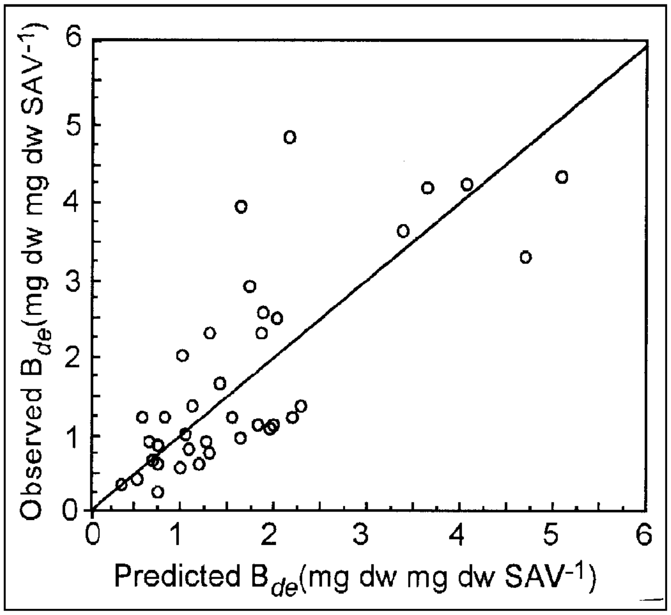

FIGURE V-6. Observed vs. Predicted Dry Weight Epiphytic Material. Comparison of observed values for total dry weight of epiphytic material (B_{de}) accumulating on artificial substrates and predicted values (from Equation V-6, B_{de} = 0.107 TSS + 0.832 B_e), using inputs of data for total suspended solids, TSS (mg l^{-1}) and epiphytic algal biomass, B_e (mg chl-*a* g dw^{-1}), from experimental pond studies (Staver 1984, Twilley et al. 1985). Line indicates one-to-one correspondence between predicted and observed epiphyte mass.

relationships. In the experimental pond studies (Staver 1984), data were collected at much higher frequencies—two to three times per week. The increased sampling frequency is thought to have contributed to the relative success in developing this relationship (Equation V-6), compared to attempts to detect similar functions from field sampling, where total suspended solids (and, perhaps, B_{de}) tend to be highly variable over short time periods, such as days.

With the relationship indicated in Equation V-6, we have a complete, calibrated, statistically significant algorithm, which can be computed in a spreadsheet format or statistical package. This spreadsheet model solves the original Equation V-1 to estimate light levels (as percent of surface PAR) at SAV leaf surfaces (I_{zs}) for any site at a particular depth that has data for dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d, and total suspended solids. The model defines percent light at the SAV leaf surface (PLL) and percent light in the water directly overlying leaves (PLW). The computations in this model can be summarized into seven steps, which require different data inputs and user decisions (Table V-1). A computer spreadsheet program for performing these calculations has been developed and is available for access and downloading in conjunction with this report through the Chesapeake Bay Program web site at www.chesapeakebay.net/tools.

SENSITIVITY ANALYSIS OF THE MODEL

The model was used to calculate PAR levels at SAV leaves for different values of dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d and total suspended solids to consider the relative contributions of each to light attenuation at 1-meter depth. The 1992 SAV habitat requirements were selected as a reference point (Batiuk *et al.* 1992; Dennison *et al.* 1993) for this analysis; plankton chlorophyll *a* was omitted from this analysis because its effect on light attenuation is accounted for with K_d. The relevant habitat requirement values (expressed in micromolar or M units for dissolved inorganic nitrogen and dissolved inorganic phosphorus) are: DIN = 10 M (mesohaline and polyhaline); DIP = 0.67 M (tidal fresh, oligohaline and polyhaline) and DIP = 0.33 M (mesohaline); K_d = 1.5 m^{-1} (mesohaline and polyhaline) and K_d = 2 m^{-1} (tidal fresh and oligohaline); and TSS = 15 mg l^{-1}. Each parameter value was varied by factors of 0.5 and 2 to calculate the percent of incident light levels in the water directly overlying SAV leaves (PLW) and the percent of incident light available at the leaf surface (PLL). This sensitivity analysis was performed for each of the Bay salinity regimes (tidal fresh/oligohaline, mesohaline and polyhaline).

The percent of surface light level available in the water overlying the SAV leaves (PLW) is regulated by K_d, varying from 22 percent in mesohaline and polyhaline regions to 13 percent in the tidal fresh and oligohaline regions. The percent surface light available at the leaf surface (PLL) ranges from 9 percent in tidal fresh and oligohaline regions to 17 percent in mesohaline and 14 percent in polyhaline regions. These differences in PLL and PLW among salinity regimes derive from differences in the habitat requirements listed above. Results of the sensitivity analysis are presented in Figure V-7, with horizontal dashed lines indicating values of PLL and PLW calculated for these habitat requirement values (Batiuk *et al.* 1992).

In terms of total light reduction, this analysis revealed that PAR levels were most sensitive, by far, to changes in K_d. This is not surprising, given the fact that K_d is an exponential coefficient. Calculated values for PLL were also responsive to variations in total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus (Figure V-7).

The asymmetry of these sensitivities results from the highly nonlinear nature of the spreadsheet model. Sensitivities to dissolved inorganic phosphorus and dissolved inorganic nitrogen were the same for the polyhaline and oligohaline areas, but PLL did not respond to changes in dissolved inorganic nitrogen in the mesohaline because DIN:DIP ratio was greater than 16 for the 1992 SAV habitat requirements in that salinity regime (Batiuk *et al.* 1992). For both the mesohaline and polyhaline regions, changes in nutrient concentration had somewhat greater effect (±1-4 percent) on PLL than did changes in total suspended solids (±1-2 percent). Note, however, that this analysis only considers effects of total suspended solids on epiphyte attenuation of light. The direct impact of total suspended solids on K_d (which is great; see Chapter IV) was not taken into account. In the tidal fresh/oligohaline region, calculated PLL was less sensitive to changes in total suspended solids and nutrients but more responsive to changes in K_d than in other salinity regimes.

Another way to consider the relative contributions of total suspended solids and dissolved inorganic nutrients to light attenuation by epiphytic material is illustrated by plotting isolumes (lines of constant light) calculated by the spreadsheet model under conditions where total suspended solids and dissolved inorganic nitrogen concentrations are varied simultaneously (Figure V-8). In general, at Z = 1 meter, changes in dissolved inorganic nitrogen have a substantial effect on the light climate (crossing isolumes) at all but the lowest total suspended solids concentrations, while decreases in total suspended solids have a significant impact only at very high dissolved inorganic nitrogen concentrations and very low PLL values. For example, at a total suspended solids concentration of 15 mgl^{-1}, a reduction in dissolved inorganic nitrogen from 15 to 5 M improves light conditions from 12 to 17 percent surface irradiance; however, at a dissolved inorganic nitrogen concentration of 20 M, a reduction in total suspended solids from 15 to 5 mg l^{-1} improves light at the SAV leaf surface only from 11 percent to 12 percent. It is obvious that such changes in total suspended

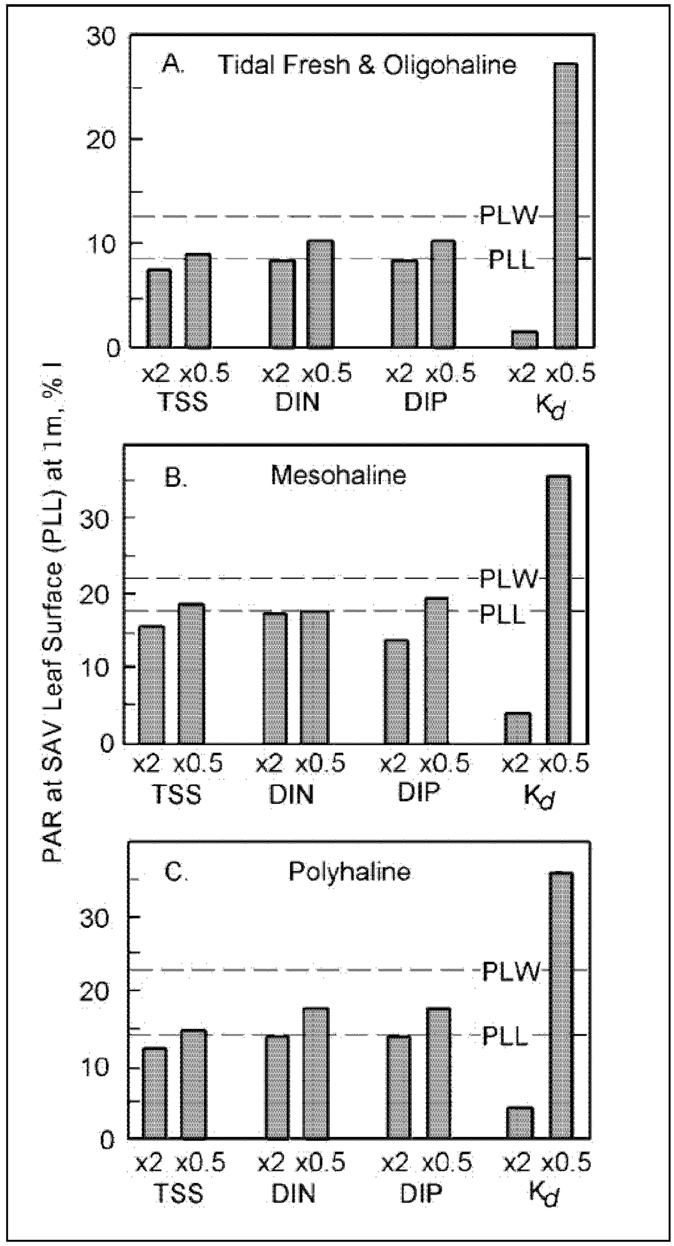

FIGURE V-7. Percent Light at the Leaf Sensitivity Analysis. Sensitivity analysis for values of percent of incident light at SAV leaf surface (PLL) calculated from the spreadsheet model (Table V-1) in response to doubling (x 2) and halving (x 0.5) concentrations of total suspended solids (TSS), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP), and values for light attenuation coefficient (K_d). Calculated values based on previously published SAV habitat requirements (Batiuk *et al.* 1992) are used as references, with values of PLL and percent incident light in water overlying SAV (PLW) shown as horizontal dashed lines for A) tidal fresh and oligohaline, B) mesohaline and C) polyhaline regions of Chesapeake Bay.

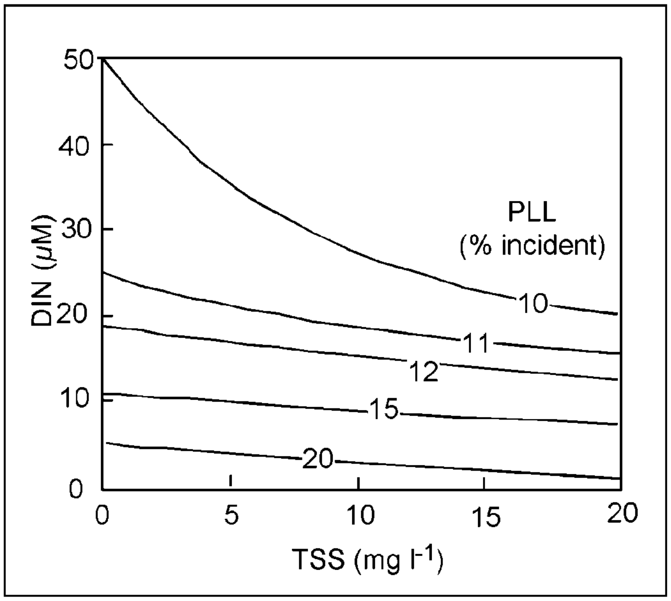

FIGURE V-8. Effects of DIN and TSS on Percent Light at the Leaf. Interacting effects of dissolved inorganic nitrogen (DIN) and total suspended solids (TSS) concentrations on percent incident light at SAV leaf surface (PLL). Family of isolumes (lines of constant light) for PLL of 10-20 percent calculated from the model described in this report for a restoration depth of 1 m (see Table V-1).

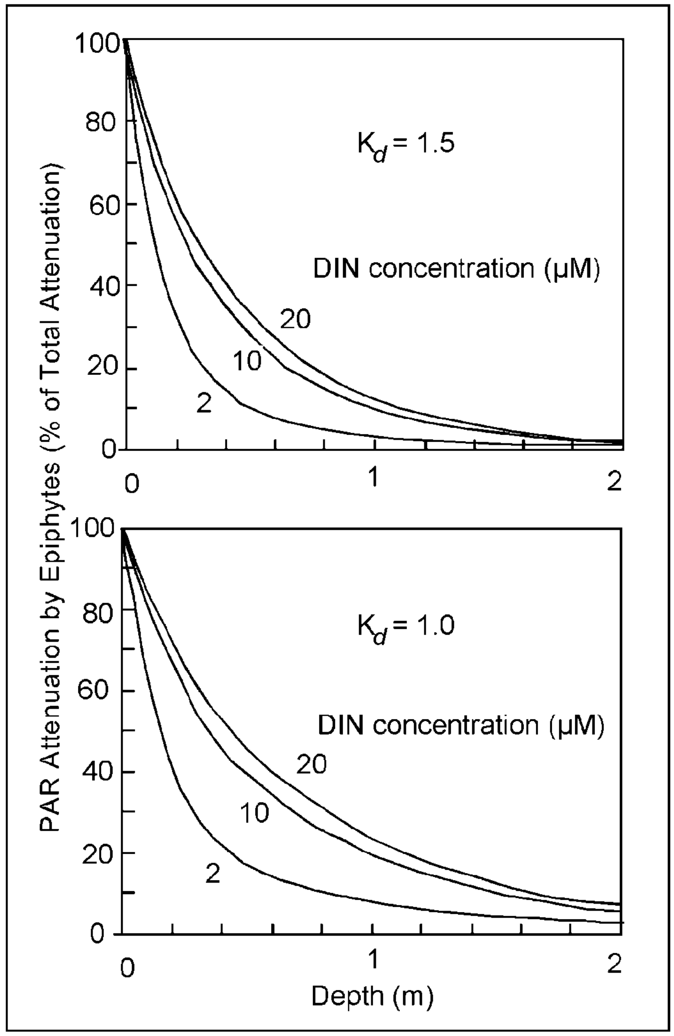

FIGURE V-9. Effects of Water Depth, DIN, and Kd on Epiphyte Contribution to PAR Attenuation. Effects of water depth, dissolved inorganic nitrogen concentration (DIN) and light attenuation (K_d) on relative contributions of epiphytes to total PAR attenuation to SAV leaves. Lines calculated from the model developed in this report (see Table V-1).

solids would also impart substantial effects on K_d; however, the purpose of this analysis was to isolate the effects on epiphytic attenuation only.

The relative contribution of epiphytic material to total PAR attenuation varies with depth and water column turbidity. In the 1992 SAV habitat requirements for the mesohaline and polyhaline regions of Chesapeake Bay (DIN = 10 M, K_d = 1.5 m^{-1}; Batiuk *et al.* 1992), PAR attenuation by epiphytic material is approximately 25 percent of the total at 0.5 m and 10 percent of the total at 1-meter depth (Figure V-9, upper panel). This contribution decreases substantially at lower ambient nutrient concentrations. At lower values of K_d (1.0 m^{-1}) and 0.5 m water depth, epiphyte contribution to total PAR attenuation increases to almost 40 percent at DIN =10 M and 20 percent at DIN = 2 M (Figure V-9, lower panel). These sensitivity calculations emphasize the fact that at $Z > 0.5$ m, epiphytic material contributes substantially less to the total shading of SAV than do materials suspended and dissolved in the overlying water. However, in many cases the additional reductions in ambient light associated with epiphytic accumulations is sufficient to reduce SAV growth below the minimum levels needed for plants to survive (e.g., Kemp *et al.* 1983; Twilley *et al.* 1985).

This spreadsheet model calculation of the percent light reaching SAV leaf surface (PLL) was applied to sites in the mainstem and tidal tributaries of Chesapeake Bay for field verification and to explore regional patterns in the estuary. Growing season median values for dissolved inorganic nitrogen, dissolved inorganic phosphorus, total suspended solids and K_d measured at Chesapeake Bay water quality monitoring stations within 2 to 5 km of existing and potential nearshore SAV habitats were compiled from the period 1985-1996 for stations in the mainstem Bay and from all monitored tidal tributary and embayment estuaries. These data are updated versions of those used for field verification analyses presented previously (Batiuk *et al.* 1992).

Results of model computations are summarized (Figure V-10) in bar graphs as mean light levels calculated at the SAV leaf surface (PLL, including epiphyte attenuation) for all sites in the estuary. Values for PLL were calculated at water depths of 1 meter and 0.5 meters (upper panel only). Results are summarized for five categories of SAV abundance: 1) "always none"; 2) "usually none"; 3) "sometimes some"; 4) "always some"; and 5) "always abundant." These categories are defined precisely in Chapter VII. Calculations are also parsed into three salinity regions of the Bay: 1) tidal fresh/oligohaline; 2) mesohaline and 3) polyhaline. No sites qualified for the "always none" category in the polyhaline region, where SAV is generally most abundant. Calculations are provided for water depth of 0.5 m in the tidal fresh/oligohaline region because of the prevalence of relatively shallow, broad and protected sites in the upper Bay.

In general, there is a consistent pattern of increasing light (PLL) with increasing probability of SAV occurrence (Figure V-10). The one exception is for the "always abundant" category in the oligohaline region (Figure V-10, upper panel). It is assumed that minimum light required for SAV survival should fall between the mean light levels associated with the "sometimes some" and "always some" categories of SAV abundance.

For the mesohaline and polyhaline regions, the mean calculated PLL values range from 20-25 percent surface irradiance for sites having SAV occurrence characterized between "sometimes" and "always." This analysis suggests that the target value of 15 percent surface irradiance for SAV minimum light requirement derived from analysis of the literature serves as a conservative but robust index of SAV habitat suitability for these regions of Chesapeake Bay.

Light requirements in the tidal fresh and oligohaline regions are more difficult to discern; however, for the same SAV occurrence categories, calculated values for PLL range from 4 to 7 percent at 1-meter water depth

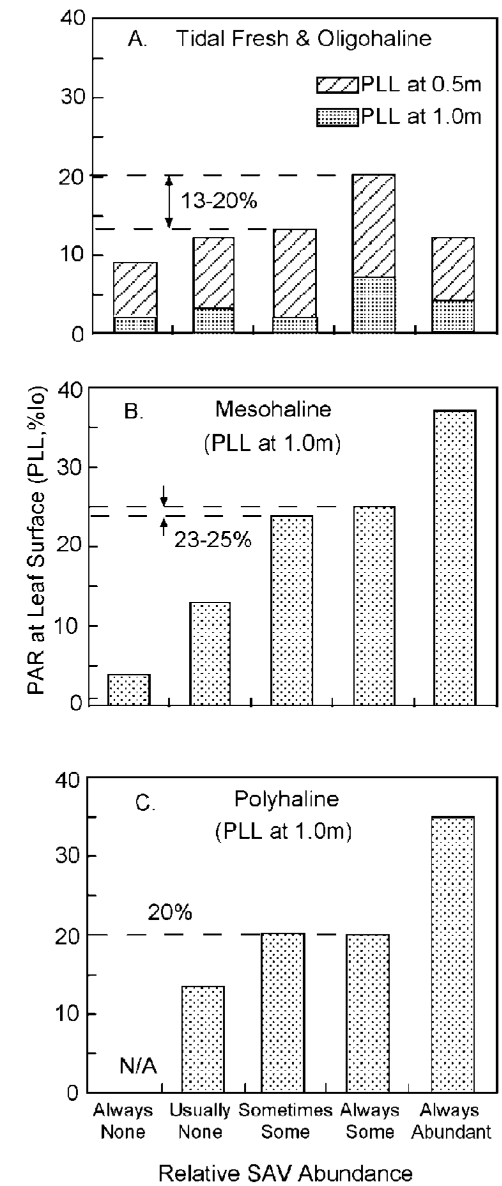

FIGURE V-10. Calculated Percent Light at the Leaf Values by Relative SAV Abundance by Salinity Regime. Calculated mean values for percent incident light at SAV leaf surface (PLL) for all water quality monitoring stations in the mainstem, tidal tributaries and embayments of Chesapeake Bay during 1985-1996 grouped into five categories of relative SAV abundance or occurrence and three salinity regimes. Values of PLL were calculated for water depth of 0.5 and/or 1.0 m using the model described in this report (see Table V-1) with input data (total suspended solids, dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d) for SAV growing season (April-October for tidal fresh, oligohaline, and mesohaline and March-May and September-November for polyhaline) of each year from the Chesapeake Bay Program water quality monitoring program. N/A indicates that there were no sites in the polyhaline region without occasional SAV presence.

and from 13-20 percent at 0.5 meters. Since the mean water depths for sites with SAV growing in these Bay regions tend to fall between 0.5 meters and 1 meter, the target value (derived from the literature review) of 9 percent surface irradiance is also very consistent with mean light conditions calculated to support minimal SAV growth. The tidal fresh and oligohaline regions of the Bay are generally the most turbid (e.g., Schubel and Biggs 1969; Keefe *et al.* 1976; Smith and Kemp 1995). The reduced consistency between light variability and SAV occurrence in this turbid region of the Bay (Figure V-10, upper panel) is consistent with observations in turbid lakes (Middleboe and Markager 1997).

Regional variations in the relative contributions of water-column and epiphyte attenuation for defining potential SAV habitats can be seen by comparing calculated values for PLL and PLW at sites pooled into different salinity regimes (Figures V-11 and V-12). In general, values of both PLL and PLW tend to increase as one moves from lower to higher salinity regions (Figure V-11; upper, middle and lower panels, respectively). Although Figure V-11 presents data for Virginia portions of the Bay only, similar patterns are evident for the Maryland waters of the Bay.

Sites in the tidal fresh and oligohaline regions appear to have greater potential effects of light attenuation by epiphytic material, as indicated by the data points falling well below the 1:1 line (Figure V-11). In these low salinity regions, almost half of the total attenuation is attributable to epiphytic materials. This is because of the higher nutrient concentrations and total suspended solids levels in lower salinity areas.

There is little difference in the relative contribution of epiphytes in the mesohaline and polyhaline regions, where the epiphyte effect [(PLW-PLL)/PLL] tends to range from 25-40 percent and increases as PLL decreases (Figure V-12). While there is a clear pattern of changing contribution of epiphyte attenuation along the estuarine salinity gradient, there is less of a marked difference in the PLL vs. PLW relationship for upper Bay (Maryland waters) compared to lower Bay (Virginia waters) areas (Figure V-12). In both cases, mean epiphyte contributions [(PLW-PLL)/PLL] range from about 20-50 percent, and they are greatest at more turbid sites. Thus, it is clear that at 1-meter water depth, potential accumulation of epiphytic material represents a significant fraction of total potential light attenuation at sites throughout Chesapeake Bay.

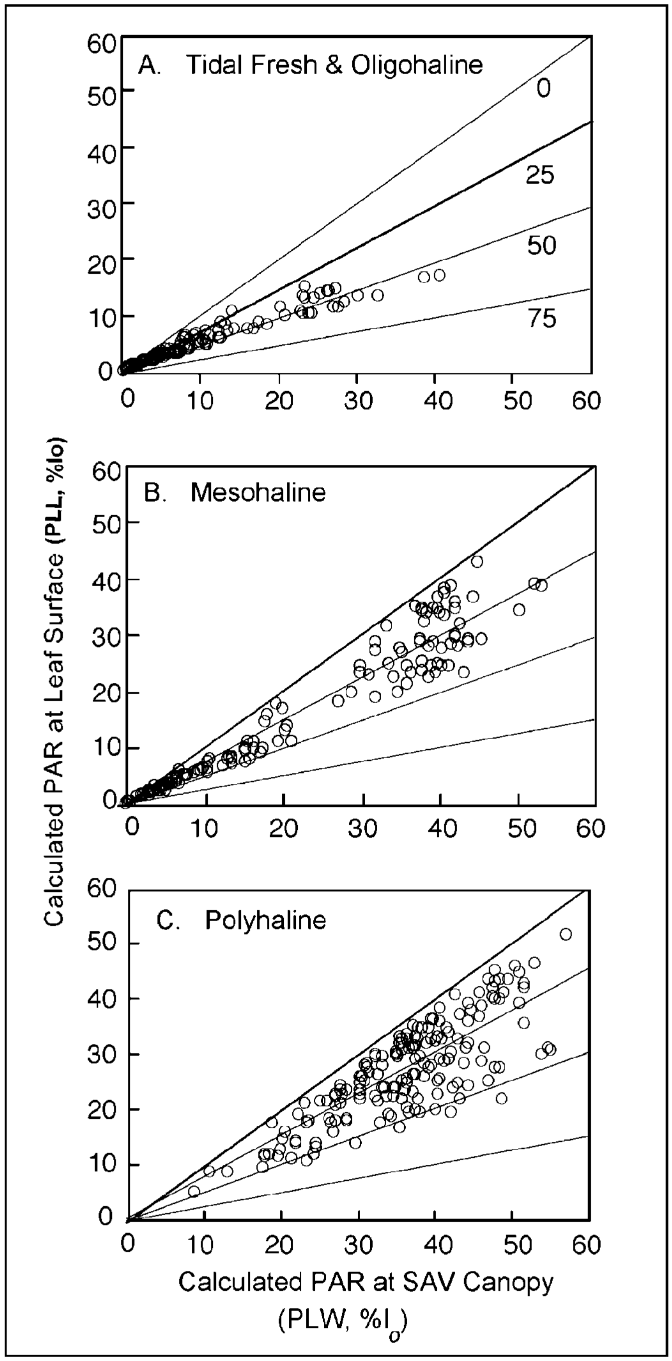

FIGURE V-11. Percent Light at Leaf vs. Percent Light Through the Water Column by Salinity Regime. Comparing values for percent surface light at SAV leaf surface (PLL) and percent surface light in water just above the SAV leaf (PLW) calculated for restoration depth Z = 1 m from the model described in this report (Table V-1) for water quality monitoring stations in Virginia portion of Chesapeake Bay for 1985-1996 in three salinity regimes. Lines indicate position of points where epiphyte attenuation reduced ambient light levels at the leaf surface by 0, 25, 50 and 75 percent.

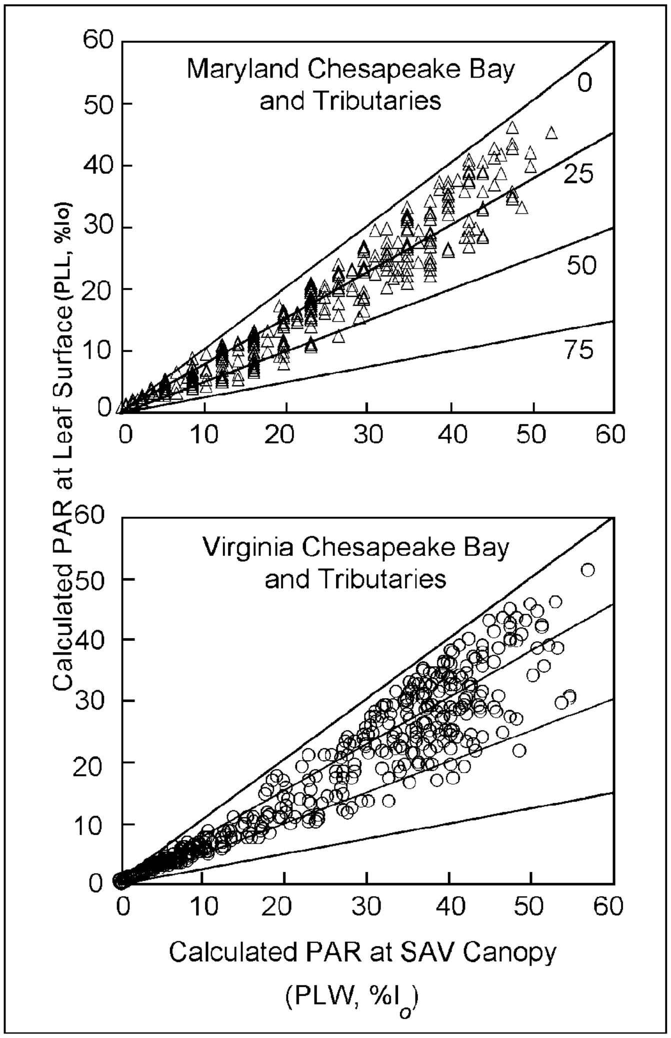

FIGURE V-12. Percent Light at the Leaf vs. Percent Light Through the Water Column, by State.
Comparing values for percent surface light (PAR) at SAV leaf surface (PLL) and percent surface light in water just above SAV leaf (PLW) for all monitored sites in the mainstem, tidal tributaries and embayments of Chesapeake Bay during 1985-1996 grouped into upper (Maryland) and lower (Virginia) estuary regions. Values of PLL and PLW were calculated for water depth of 1 m using the model described in this report (Table V-1) with input monitoring data (total suspended solids, dissolved inorganic nitrogen, dissolved inorganic phosphorus, K_d) for the SAV growing season of each year. Lines indicate position of points where epiphyte attenuation reduced ambient light levels at the leaf surface by 0, 25, 50 and 75 percent.

CONCLUSIONS

The model developed in this chapter to calculate contributions of water-column and epiphytic materials to light attenuation under different water quality conditions works well for sites throughout Chesapeake Bay, including its tidal tributaries across all salinity regimes. Values for PLL calculated from water quality data vary widely among sites throughout the Bay. The model relies on a combination of empirical relationships derived from field studies and experimental systems and numerical computations from a well-calibrated ecosystem process model. Much of the information on which the model is based comes from the measurements and analyses done in the mesohaline and polyhaline regions of Chesapeake Bay; particularly studies of two SAV species—*Potamogeton perfoliatus* and *Z. marina* (e.g., Staver 1984; Twilley *et al.* 1985; Goldsborough and Kemp 1988; Neckles 1990; Moore 1996; Sturgis and Murray 1997). This is due to limited comparable data from lower salinity tidal habitats.

The model is easily used and is amenable to simple spreadsheet computations on diverse platforms. It has substantial utility as a screening tool to assess trends in SAV habitat conditions at individual sites, based on changes in water quality variables. In ecosystems such as Chesapeake Bay, where a broad monitoring program exists to support efforts to improve water quality for restoring SAV to degraded habitats, this model provides an additional important tool to guide management efforts.

CHAPTER VI

Beyond Light: Physical, Geological and Chemical Habitat Requirements

Light availability has been identified as the major factor controlling the distribution and abundance of SAV in Chesapeake Bay (e.g., Dennison *et al.* 1993). Therefore, parameters that can affect the light availability in an environment (total suspended solids, chlorophyll *a* concentration, epiphyte biomass) are commonly included in predictions of the suitability of certain areas for SAV growth. Several other parameters that have the potential to override the light requirements of the plants are not often considered when determining the suitability of a site for SAV growth (Livingston *et al.* 1998). For example, very high wave energy may prevent SAV from becoming established (due to the drag exerted on the plants and/or the constant sediment motion), even when the light requirements are met (Clarke 1987).

This chapter discusses physical, geological and chemical factors that affect the suitability of a site for SAV growth. These factors differ from those described in chapters III, IV and V in that the parameters considered there *modify* the light requirements of SAV. The parameters discussed in the present chapter *override* the established SAV light requirements. The parameters addressed here (waves, currents, tides, sediment organic content, grain size and contaminants) can influence the presence/absence of SAV in a certain area, independently of light levels. Figure VI-1 shows how previously established SAV habitat requirements (light attenuation coefficient, dissolved inorganic nutrients, chlorophyll *a*, total suspended solids and epiphytes) as well as the parameters discussed in this chapter (waves, currents, tides, sediment characteristics and chemical contaminants) can affect the distribution of SAV.

FEEDBACK BETWEEN SAV AND THE PHYSICAL, GEOLOGICAL AND CHEMICAL ENVIRONMENTS

SAV beds can reduce current velocity (Fonseca *et al.* 1982; Fonseca and Fisher 1986; Gambi *et al.* 1990; Koch and Gust 1999; Sand-Jensen and Mebus 1996; Rybicki *et al.* 1997), attenuate waves (Fonseca and Cahalan 1992; Koch 1996), change the sediment characteristics (Scoffin 1970; Wanless 1981; Almasi *et al.* 1987; Wigand *et al.* 1997) and even change the height of the water column (Powell and Schaffner 1991; Rybicki *et al.* 1997). In turn, these SAV-induced changes can affect the productivity of the plants. Therefore, a complex feedback mechanism exists between SAV and the abiotic conditions of the habitat they colonize, making it difficult to attribute the distribution of SAV to only one factor, such as light.

By reducing current velocity and attenuating waves, SAV beds create conditions that lead to the deposition of small (inorganic) and low-density (organic) particles within meadows or canopies (Grady 1981; Kemp *et al.* 1984; Newell *et al.* 1986). This in turn can affect the availability of light (Moore *et al.* 1994), nutrients (Kenworthy *et al.* 1982) and compounds that can be toxic to SAV (phytotoxins), such as sulfide in the sediments (Carlson *et al.* 1994; Holmer and Nielsen 1997). Therefore, all these parameters contribute, to some degree, to the regulation of SAV growth.

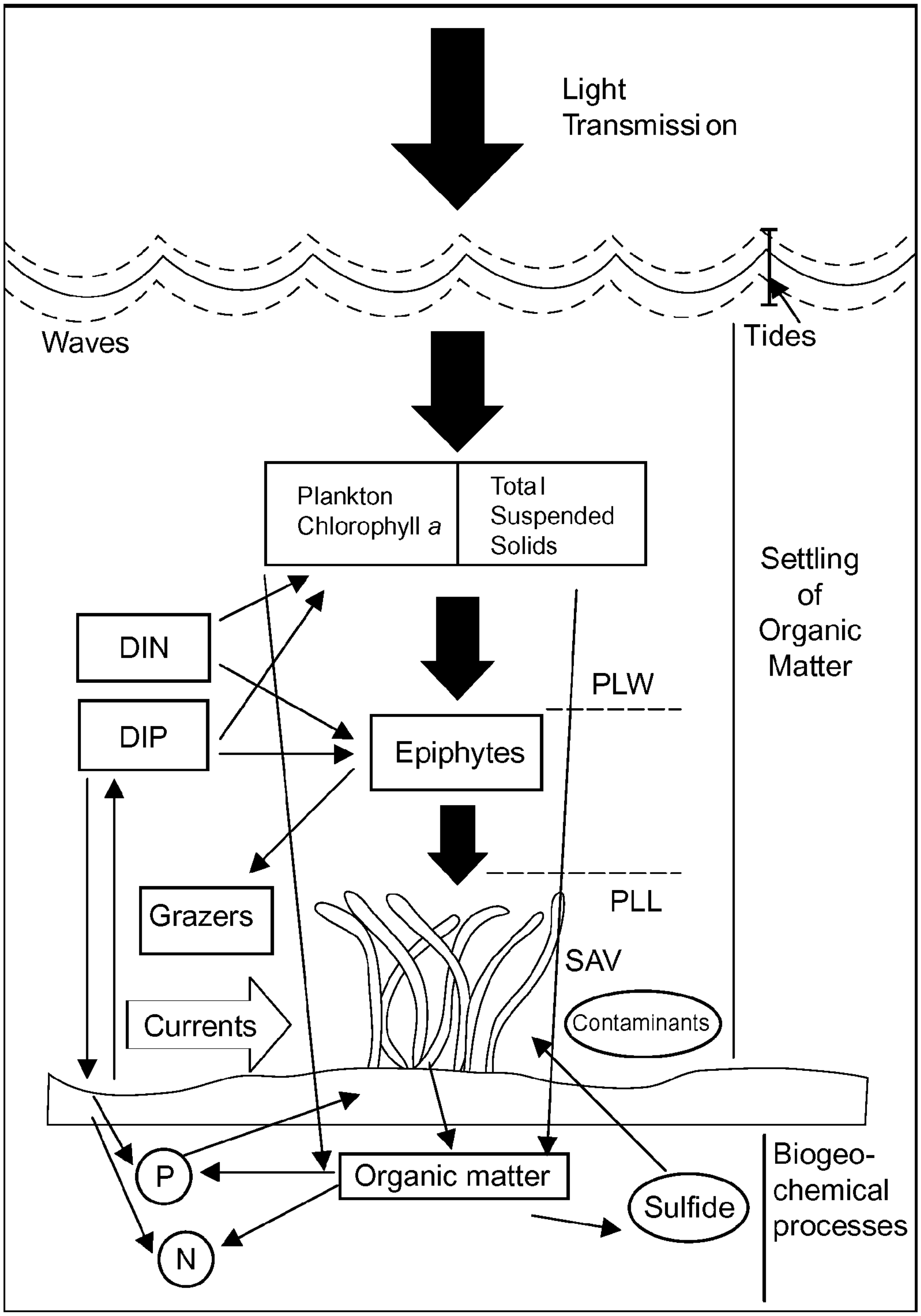

FIGURE VI-1. Interaction between Light-Based, Physical, Geological and Chemical SAV Habitat Requirements. Interaction between previously established SAV habitat requirements, such as light attenuation, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), chlorophyll *a*, total suspended solids (TSS) and other physical/chemical parameters discussed in this chapter (waves, currents, tides, sediment organic matter, biogeochemical processes). P = phosphorus; N = nitrogen; PLW = percent light through water; PLL = percent light at the leaf.

When plant density is low, the attenuation of current velocity and wave energy is also low. This results in little accumulation of organic matter and, subsequently, little change in sediment nutrient and phytotoxin concentrations. Light availability may also be low, due to the resuspension of sediments. Oxygen demand of the roots (to counteract the detrimental effect of the phytotoxins) may also be low, due to reduced photosynthetic biomass.

In SAV beds with high shoot density, water flow is reduced and more particles are deposited, leading to higher light, nutrient and phytotoxin availability than in less dense beds. The SAV density may reach a point where so much organic matter is trapped that the resulting high phytotoxin levels are no longer tolerated by the plants, and they may start dying back (Roblee *et al.* 1991; Carlson *et al.* 1994; Holmer and Nielsen 1997). At that point, the reduction in density may lead to higher water flow, reduced organic matter accumulation and reduced phytotoxin levels in the sediment. This feedback mechanism (hydrodynamics → sediment characteristics → plant biomass → hydrodynamics) may assure the health of marine and higher salinity estuarine SAV populations over time. The above mechanism may be less applicable for SAV colonizing low-salinity estuarine areas, because sulfide concentrations do not reach levels as toxic as those in marine environments. However, low-salinity species can also be susceptible to sulfide, as shown by the decreased growth rates of *Potamogeton pectinatus* when sulfide was added to the sediments (van Wijk *et al.* 1992).

SAV AND CURRENT VELOCITY

SAV beds reduce current velocity by extracting momentum from the moving water (Madsen and Warnke 1983). The magnitude of this process depends on the density of the SAV bed (Carter *et al.* 1991; van Keulen 1997), the hydrodynamic conditions of the area (stronger reduction in flow in tide-dominated vs. wave-dominated areas; Koch and Gust 1999) and the depth of the water column above the plants (Fonseca and Fisher 1986). The highest reduction in current velocity occurs in dense, shallow beds exposed to tide-dominated conditions (unidirectional flow). Currents in SAV beds can be 2 to 10 times slower than in adjacent unvegetated areas (Ackerman 1983; Madsen and Warncke 1983; Carter *et al.* 1988; Gambi *et al.* 1990; Rybicki *et al.* 1997).

Positive Effects of Reduced Current Velocity

The advantages of reduced water flow in SAV beds include the following:

1) Reduced self-shading due to the more vertical position of the blades in beds resulting from reduced drag on SAV leaves (Fonseca *et al.* 1982);

2) Increased settlement of organic and inorganic particles, increasing the light availability and the sediment nutrient concentration (Kenworthy *et al.* 1982; Ward *et al.* 1984; references in the review by Fonseca 1996). Notice that this can also lead to a disadvantage due to increasing sulfide concentration in marine/higher salinity estuarine habitats (Koch 1999) (see "Negative Effects of Reduced Current Velocity").

3) Lower friction velocities at the sediment surface than in unvegetated areas (Fonseca and Fisher 1986) reducing sediment resuspension and total suspended solids concentrations and increasing light availability (references in the review by Fonseca 1996).

4) High residence time, allowing molecules of dissolved nutrients to stay in contact with SAV leaves and epiphytes for longer periods of time, therefore increasing the likelihood of being taken up. As a result, high residence time reduces the nutrient concentration in the water column (Bulthuis *et al.* 1984), perhaps limiting epiphytic growth, which would otherwise lead to further reduction in light attenuation (see Chapter V). Epiphytes and SAV will compete for nutrients in the water column, while only SAV can remove nutrients from the sediments. Therefore, the SAV should not become as nutrient-limited as epiphytes since they primarily use nutrients from the sediments.

5) Increased settlement of spores of algae and larvae of a variety of organisms, resulting in higher species diversity of invertebrates and algae in SAV canopies than in adjacent unvegetated areas (Homziak *et al.* 1982).

Negative Effects of Reduced Current Velocity

The points listed above illustrate the potential positive effects of reduced current velocity in SAV beds. Alternately, reduced water flow can also have detrimental effects:

1) Concentration of phytotoxins will increase in estuarine/marine sediments (Koch 1999). The concentration of phytotoxins in the sediment leads to an increased oxygen demand by the roots which, if not met due to poor light availability, has the potential to kill the plants (Robblee *et al.* 1991; Carlson *et al.* 1994; Nepf and Koch 1999).
2) Thicker blade diffusion boundary layers will form under reduced current velocity in SAV beds (Koch 1994). The diffusion boundary layer is a thin (a few μm) layer of water on the surface of any submersed object (including plants) where the transport of solutes (e.g. carbon needed for photosynthesis or oxygen produced by photosynthesis) is dominated by viscous forces (i.e., by diffusion).

Increases in the thickness of this diffusion boundary layer lead to a longer diffusional path (or thick diffusion boundary layer) for carbon molecules to move from the water column to the SAV leaf, where they are used for photosynthesis. As the current velocity decreases, a critical maximum diffusion boundary layer thickness, where the flux of carbon to the plant is slower than the flux needed for the plant to support maximum photosynthesis, can be reached. The critical diffusion boundary layer thickness was estimated to be 280 μm for *Thalassia testudinum* and 98 μm for *Cymodocea nodosa* (Koch 1994).

If a plant is exposed for long periods of time to diffusion boundary layer thicknesses greater than the critical diffusion boundary layer thickness, growth can decline, due to carbon limitation independent of the light levels at the site. The length of time that a plant can survive under such conditions depends on the internal carbon reserves in the plant tissue and how fast these reserves can be accessed (Koch 1993). This has not yet been determined for most SAV species and has the potential to be important in areas where marinas and other structures may cause stagnant conditions in SAV habitats.

Some estuarine and freshwater SAV species, such as *Potamogeton pectinatus,* are capable of colonizing relatively stagnant waters (like those found in ponds) due to a physiological adaptation: the release of H^+ on one side of the blade (polar leaves) reduces the pH in the diffusion boundary layer (Prins *et al.* 1982). This decrease in pH shifts the carbon balance toward carbon dioxide (CO_2), increasing local diffusion boundary layer CO_2 concentration and, therefore, increasing the flux of CO_2 into the plant. Other SAV can also incorporate CO_2 from sediment porewater, where dissolved inorganic carbon concentrations are usually much higher than open-water concentrations (Sondergaard and Sand-Jensen 1979; Madsen 1987). The CO_2 incorporated by the roots is then transported to the photosynthetic tissue via the lacunae system (Madsen and Sand-Jensen 1991). For a detailed discussion on mechanisms aquatic plants developed to deal with reduced carbon fluxes due to thick diffusion boundary layers, see Jumars *et al.* (accepted).

Epiphytes and Current Velocity

Although epiphytes are usually seen as organisms that are detrimental to SAV growth, the very early stages of epiphytic colonization on SAV leaves have the potential to be beneficial for the plants (Koch 1994). Very low densities of epiphytes (only visible under a microscope) may disrupt the diffusion boundary layer enhancing the flux of carbon to the blade (Koch 1994). As epiphytes compete for light, nutrients and carbon, later stages of epiphytic colonization (when the epiphytic layer is too dense to disrupt the diffusion boundary layer) become detrimental to SAV growth. At the community level, epiphytes will contribute to the reduction in current velocity (due to increased leaf drag) which leads to the positive aspects listed above (see "Positive Effects of Reduced Current Velocity"). Therefore, in some aspects, epiphytes can have positive effects on SAV communities, although the negative effects of epiphytes on SAV leaves (light attenuation and increased drag on the leaves, potentially dislodging them at high flows) also need to be kept in perspective.

Epiphytes on SAV leaves may also respond to water flow independently of the SAV response to flow. In a study using acrylic plates, maximum periphyton biomass was observed at intermediate current velocities. Diatoms were dominant under high current conditions while a green alga was dominant at lower current velocities (Horner *et al.* 1990). In a mesocosm experiment, epiphyte biomass on *Vallisneria americana* increased with current velocity (Merrell 1996). Therefore, a second order of complexity (water flow) needs be added to future refinements of the model evaluating the effect of epiphytes on light available to SAV leaves (see Chapter V).

Current Velocity SAV Habitat Requirements

From the positive and negative effects of the reduced current velocities found in SAV beds, it can be concluded that these plants could benefit from intermediate current velocities (Boeger 1992; Koch and Gust 1999; Merrell 1996; Koch 1999). Extremely low water flows could increase the blade diffusion boundary layer thickness as well as the accumulation of organic matter in the sediment leading to carbon starvation or death due to high phytotoxin concentrations in the sediment, respectively. In contrast, extremely high water flow has the potential to 1) increase drag above a critical value where erosion of the sediment and plants occurs, 2) reduce light availability through resuspension of sediment and self-shading and 3) decrease the accumulation of organic matter, leading to reduced nutrient concentration in the sediments.

A literature review revealed that 1) the range of current velocities tolerated by marine SAV species lies between approximately 5 and 100 cm s^{-1} (physiological and mechanical limits, respectively); 2) the range of current velocities tolerated by freshwater SAV species seems generally to be lower than that for the marine species; and 3) some freshwater SAV species can tolerate extremely low current velocities (Table VI-1). This may be due to alternative mechanisms of carbon acquisition present in these freshwater plants but not in marine plants (see "Negative Effects of Reduced Current Velocity").

Survival of SAV in high current velocity environments may be possible if the development of seedlings occurred under conditions of slow current velocity in space (e.g., a protected cove) or time (e.g., a low water discharge period). Once a bed is established under such conditions, it can expand into adjacent areas with higher currents due to the reduced currents at the edge of the bed or persist during times of higher water flow. Therefore, the stage of the plants (for example, seeds, seedlings, vegetative shoots, reproductive shoots) also needs to be taken into account when considering if current velocity is above or below the established requirement for growth and distribution. Based on the literature review presented here, no data are available on the current velocity requirements of plants other than those found in well-established beds.

In summary, intermediate current velocities between 10 and 100 cm s^{-1} are needed to support the growth and distribution of healthy marine SAV beds. These requirements are lower for freshwater/estuarine SAV species—between 1 and 50 cm s^{-1}—especially for those with polar leaves. If currents are above or below these critical levels, the feedback mechanisms in the system may become imbalanced and possibly lead to the decline or even complete loss of the vegetation. Although some of the feedback mechanisms between SAV beds and current velocity involve light availability through the effects of resuspension of sediments, self-shading and epiphytic growth, extreme currents alone can limit the growth of SAV. Therefore, current velocity should be considered as a key SAV habitat requirement.

SAV AND WAVES

As waves propagate over SAV beds, wave energy is lost (Fonseca and Cahalan 1992; Koch 1996). This is due to the same mechanism that causes SAV beds to reduce current velocities–loss of momentum (Kobayashi *et al.* 1993). The efficiency with which waves are attenuated by SAV beds depends on the water depth (Ward *et al.* 1984; Mork 1996), the current velocity (Stewart *et al.* 1997), leaf length (Fonseca and Cahalan 1992) and the type of vegetation (canopy or meadow) (Elwany *et al.* 1995; Mork 1996; Stewart *et al.* 1997).

Wave attenuation is strongest in dense SAV beds due to increased drag and in meadows (where most of the biomass is found close to the sediment surface) colonizing shallow waters, where plant biomass takes up a large portion of the water column. Canopy-forming species that have long stems and concentrate most of their biomass, and consequently drag, on the water surface of a relatively deep water body have the tendency to oscillate with the waves. Acting as though imbedded in the waves, canopy-forming species impose little drag on them (Seymour 1996) and, therefore, have little effect on wave attenuation.

The effect the constant motion waves imposes on plants may lead to the breakage of the plants (Idestam-Almquist and Kautsky 1995; Stewart *et al.*

TABLE VI-1. Minimum and maximum current velocities required for SAV growth and distribution.

Current	Species	Source
Minimum current velocities required to saturate photosynthesis		
Current	**Species**	**Source**
> 0.04 cm s^{-1}	*Potamogeton pectinatus* *	Madsen and Sondergaard 1983
> 0.08 cm s^{-1}	*Callitriche stagnalis*	Westlake 1967
> 0.5 cm s^{-1}	*Ranunculus pseudofluitans*	Westlake 1967
> 3 cm s^{-1}	*Zostera marina*	Koehl and Worcester 1991
> 5 cm s^{-1}	*Ranunculus pencillatus*	Werner and Wise 1982
> 5 cm s^{-1}	*Thalassia testudinum*	Koch 1994
> 13 cm s^{-1}	*Cymodocea nodosa*	Koch 1994
> 16 cm s^{-1}	*Z. marina*	Fonseca and Kenworthy 1987
Maximum currents at which the following species occur		
Current	**Species**	**Source**
< 7 cm s^{-1}	*Vallisneria americana*	Merrell 1996
< 45 cm s^{-1}	*Ranunculus pencillatus*	Werner and Wise 1982
< 50 cm s^{-1}	*Zannichellia palustris*	Sculthorpe 1967
< 50 cm s^{-1}	*Z. marina*	Conover 1964
< 120 cm s^{-1}	*Z. marina*	Scoffin 1970
< 150 cm s^{-1}	*Z. marina*	Fonseca *et al.* 1982
< 180 cm s^{-1}	*Z. marina*	Phillips 1974

* Indicates species for which leaf polarity has been confirmed.

1997). This effect has been observed to be more severe for a canopy-forming species (*Myriophyllum spp.*) than for a meadow-forming species (*Vallisneria spp.*; Stewart *et al.* 1997). Breakage of underwater plants exposed to waves is inversely related to current velocity. As current velocity increases, the plants lie closer to the sediment surface and are, therefore, less affected by the orbital motion of the waves (Stewart *et al.* 1997).

Table VI-2 summarizes the capacity of marine SAV species to attenuate waves under a variety of field and laboratory conditions. The values obtained in the lab are much higher than those obtained in the field, because the meadow-forming plants used in the lab experiments occupied the entire water column, and wave attenuation is positively correlated with the percentage of the water column occupied by the vegetation.

Effects of High Wave Energy

The impact of high wave energy on SAV can be direct or indirect. The direct impact of waves on SAV can be seen when waves (in combination with currents) erode the edges of an SAV bed (Clarke 1987) or when portions of the plants are removed by storm-generated (Thomas *et al.* 1961; Eleuterius and Miller 1976; Rodriguez *et al.* 1994; Dan *et al.* 1998) or boat-generated waves (Stewart *et al.* 1997). Indirect consequences of wave energy in SAV beds include sediment resuspension, changes in sediment grain size, mixing of the water column and epiphytic growth. If the capacity of an SAV bed to attenuate waves is reduced, for example, due to a reduction in shoot density because of clam dredging or eutrophication, the underlying sediment will become more vulnerable to erosion, and higher concentrations of suspended

TABLE VI-2. Attenuation of wave energy in meadow-forming marine SAV beds.

Attenuation of Wave Energy	Wave Period (seconds)	Site	Species	Comments	Source
1.6 %	0.35	Field	*Thalassia*	Within SAV bed	Koch 1996
7.7 %	0.35	Field	*Thalassia*	Edge of SAV bed	Koch 1996
43 %	0.4 and 0.7	Flume*	*Zostera*	1 m into SAV bed	Fonseca and Cahalan 1992
43 %	0.4 and 0.7	Flume*	*Syringodium*	1 m into SAV bed	Fonseca and Cahalan 1992
44 %	0.4 and 0.7	Flume*	*Halodule*	1 m into SAV bed	Fonseca and Cahalan 1992
44 %	0.4 and 0.7	Flume*	*Thalassia*	1 m into SAV bed	Fonseca and Cahalan 1992

* Plants (meadow-formers) occupied the entire water column.

sediment particles can be expected in the water. This is especially true for SAV beds in which fine particles have accumulated over time. These sediments may be resuspended at lower wave energy than the coarser sediments outside the SAV bed (Posey *et al.* 1993).

Wave attenuation and sediment resuspension in vegetated areas depend on the water levels above the plants. At low tide, wave energy is reduced to a greater extent than during high tide (Ward *et al.* 1984). Resuspension of fine particles will alter the grain size distribution of the sediment. In areas of high wave exposure, sediments are coarser, which leads to lower nutrient concentration in the sediment and, consequently, lower root biomass (Idestam-Almquist and Kautsky 1995). By contrast, the above-ground biomass of *Potamogeton pectinatus* depends directly on wave exposure; shoots are shorter in areas with high wave exposure than in areas with low wave exposure (Idestam-Almquist and Kautsky 1995).

In Chesapeake Bay, shore erosion (caused by wave action) contributes 13 percent of the total suspended matter in the upper Bay and 52 percent in the middle Bay (Biggs 1970). Perhaps, before the decline of SAV in this area, SAV protected the coastlines from the direct impact of waves. Ward *et al.* (1984) observed that in shallow (< 2 meters) unvegetated areas in the Choptank River, total suspended solids concentrations increased tenfold when the wind came from the direction of highest fetch and was >25 km h^{-1}, but the increased total suspended solids concentrations dissipated within 24 hours after the storm. As the wind intensifies, wave period and wave length increase leading to deeper wave mixing depths (Chambers 1987). The small grain size sediments are the first to become resuspended. Therefore, if wave energy increases in an SAV bed, a shift toward coarser sediments will occur. The consequences of this shift are addressed below, in "SAV and the Sediments It Colonizes."

SAV growth and distribution seems to be limited by high, but not low wave energy (Dan *et al.* 1998; Table VI-3). However, high wave exposure can also benefit the plants by reducing the epiphytic biomass (Strand and Weisner 1996; Kendrick and Burt 1997; Weisner *et al.* 1997). In high wave exposure areas, where sediments are constantly being shifted and grain size may be skewed toward coarser particles, SAV may not be able to become established due to the balance between the anchoring capacity of the roots and the drag exerted on the leaves. High wave exposure also leads

TABLE VI-3. Quantitative and qualitative descriptions of wave tolerance for Chesapeake Bay species.

Species	Wave Tolerance	Source
Canopy formers		
Myriophyllum spicatum	Wave limited	Rawls (1975), Stewart *et al.* 1997
Zannichellia palustris	Wave limited	Stevenson and Confer 1978
Flowering structures of *Ruppia maritima*	Wave sensitive	Joanen and Glasgow 1965
Meadow formers		
Zostera marina	2 m waves	Dan et al. 1998
Potamogeton pectinatus	Wave tolerant	Hannan 1967
Vallisneria americana	More wave tolerant than *Myriophyllum*	Stewart *et al.* 1997

to reduced light availability due to increased sediment resuspension, but this may be compensated by the lower epiphytic biomass on the leaves of wave-exposed plants. The mechanism that allows for reduced epiphytic biomass on plants exposed to high wave energy is not well understood. It could be due to the rubbing of the blades against each other.

Wave Mixing Depth Effects on SAV Minimum Depth Distributions

The minimum depth of distribution of aquatic plants in lakes with good water quality has been correlated to the resuspension of sediments by waves resulting in the scouring of sediments, uprooting of plants and increased turbidity (Figure VI-2). Consequently, Chambers (1987) suggested that the minimum depth distribution (Z_{min}) of aquatic plants can be determined by the wave mixing depth (Z_{wave}), which extends to a depth equal to half the wavelength (L),

$$Z_{min} = Z_{wave} = \frac{L}{2} \qquad \text{(VI-1)}$$

L can be calculated from the wave period (T) using the following equation:

$$L = \frac{gT^2}{2\pi} \qquad \text{(VI-2)}$$

where g is acceleration of gravity (9.805 m s^{-2}). Equation VI-2 is a standard equation for waves propagating over depths larger than half the wavelength (i.e., before they "feel the bottom" and define Z_{min}; see Equation VI-1). The wave period (T) for these waves can be predicted according to the following equation:

$$T = [\frac{0.46W}{g}][\frac{gF}{W^2}]^{0.28} \qquad \text{(VI-3)}$$

where W is the wind velocity (m s^{-1}) and F is the effective fetch (m). These equations allow for the prediction of the wave mixing depth (Z_{wave}) in shallow SAV habitats.

In relatively exposed areas at the mouth of Chesapeake Bay (Timble Shoal Entrance and Timble Shoal Light), wave periods (T) range between 4 and 13 seconds (Boon *et al.* 1996). These values are typical for wind- generated waves. Marine SAV can colonize such areas, as seen in the *Thalassia testudinum* beds offshore of the Florida Keys (Koch 1996), the *Cymodocea nodosa* beds in the Mediterranean (Koch 1994) and the *Posidonia oceanica* beds in many areas in Australia. In the shallower, more protected SAV habitats in Chesapeake Bay, waves with smaller periods (ripples) can be expected. Figure VI-3a shows the wave mixing depth for ripples and wind-generated waves while Figure VI-3b shows more details for ripples, typical for shallow, semi-enclosed SAV habitats.

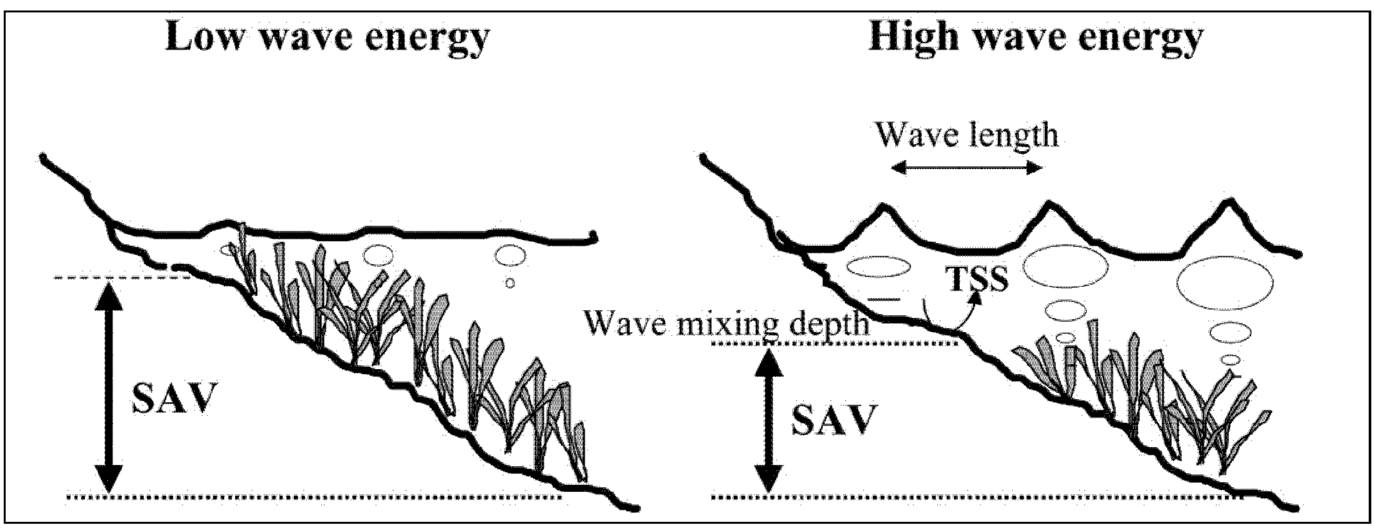

FIGURE VI-2. Wave Energy Effects on SAV Vertical Depth Distributions. The vertical distribution of SAV beds can be shifted into deeper waters due to wave energy. Waves can constantly shift sediments preventing the colonization of the area or resuspend sediments, contributing to increased total suspended solid (TSS) concentrations, which leads to reduced light levels. The zone where waves do not allow SAV to colonize is defined as the depth equivalent to half the wavelength.

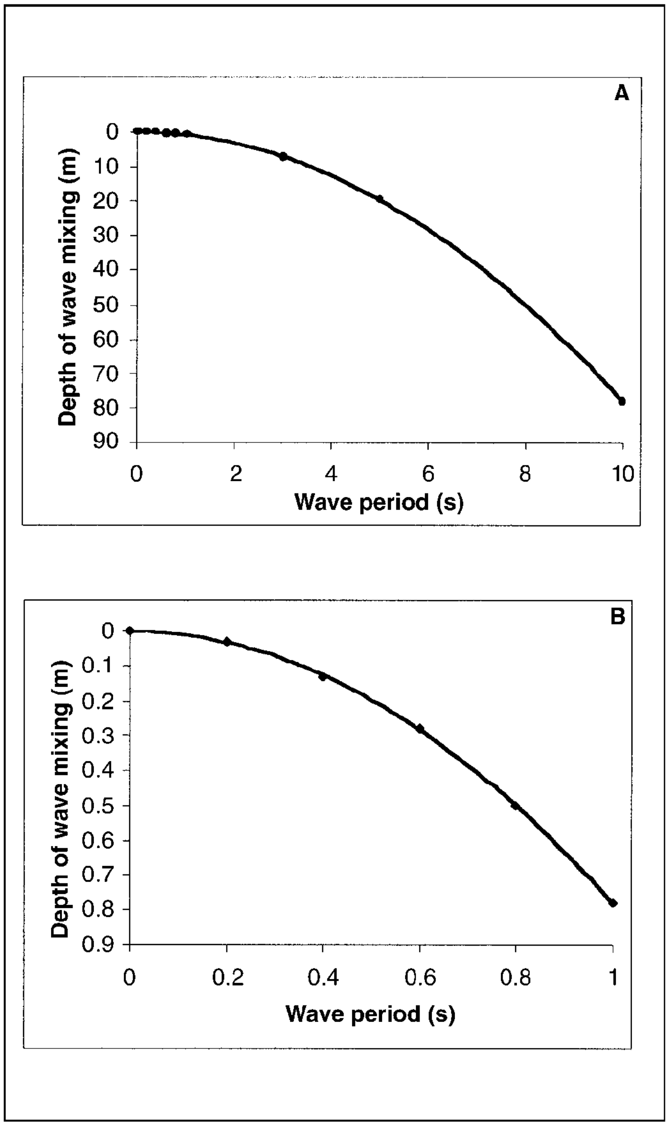

FIGURE VI-3. Wave Period/Depth of Wave Mixing Relationship. Depth of wave mixing (or minimum depth of distribution of SAV) under a variety of wave conditions. Wind-generated waves are typical for relatively exposed areas (A) while ripples are typical for shallow coastal areas. SAV occur in habitats characterized by both wave types. Depth of wave mixing for waves periods more characteristic of SAV habitats in Chesapeake Bay are illustrated in B.

Wave Exposure Habitat Requirements

Wave mixing depth and tides have a potentially confounding effect on the minimum depth of SAV distribution. As will be discussed below (see "SAV and Tides"), due to the lack of resistance of most SAV species to dessication, tides tend to force SAV to colonize deeper waters, where exposure to the air is less likely. If waves also force the SAV to inhabit deeper waters due to sediment resuspension in areas shallower than the wave mixing depth (Figure VI-2), then the minimum depth of distribution of SAV beds should be determined by the mean low water (tide) plus the wave mixing depth (see "SAV and Tides"). This can be visualized by imagining the water level in Figure VI-2 fluctuating vertically with the tides as the waves continue to propagate onshore. No data are available to verify this hypothesis.

Although waves have the potential to force SAV to colonize deeper areas (Figure VI-2) and tides may enhance this minimum limit of colonization, no 'wave exposure habitat requirement' can yet be established for SAV in Chesapeake Bay. Wave exposure indexes (based on fetch and wind intensity) have been suggested for lake environments (Keddy 1982) and recently also for an estuarine area (Murphey and Fonseca 1995; Fonseca and Bell 1998), but further research is needed to understand the effect of waves on the ecology and distribution of SAV beds. As high wave exposure has the potential to override other light requirements (K_d and epiphyte biomass) or to completely eliminate SAV from high wave exposure areas, it should be addressed as a SAV habitat requirement in the near future. Fonseca and Bell (1998) were able to determine the maximum wave exposure tolerated by SAV in Pamlico Sound, North Carolina, but when the same methodology was applied to Chesapeake Bay, no conclusive results could be obtained (Chiscano, in preparation). This difference could be due to the higher fetches in Chesapeake Bay than in Pamlico Sound, the presence of sand bars offshore from SAV beds (the model used does not take into account bottom bathymetry) or the erosion of the marshes which changes the sediment characteristics in SAV habitats, potentially limiting the distribution of SAV (see "SAV and the Sediments It Colonizes").

SAV AND TURBULENCE

Turbulence consists of temporally and spatially irregular water motion superimposed on the larger flow pattern. It forms at such boundaries as the sediment surface or the surface of SAV leaves. It is then transferred from larger to smaller scales (eddy sizes). In SAV beds, the distance between SAV shoots determines the size of the turbulence scale/eddies (Anderson and Charters 1982; Nowel and Jumars 1984; Ackerman and Okubo 1993). Turbulence in these plant communities can be generated and rescaled, i.e., shifting the scale of the eddies formed in a SAV bed (Anderson and Charters 1982; Gambi *et al.* 1990; Ackerman and Okubo 1993; Koch 1996). Since mass transfer of nutrients and carbon in the water takes place by eddy diffusion in turbulent flows (Sanford 1997), turbulence has the potential to be of extreme ecological importance in SAV beds. Turbulence also may affect the dispersion of particles such as pollen, larvae, seeds and spores in the beds. Unfortunately, the effect of turbulence on these plants is poorly understood.

The observations of turbulence in SAV beds may seem contradictory. A region of high turbulence levels can be observed at the canopy-water interface (Gambi *et al.* 1990). Increased turbulence within the vegetation has also been observed during a monami, high-amplitude blade waving (Grizzle *et al.* 1996). By contrast, reduced turbulent mixing also during a monami in a *Zostera marina* bed has been reported by Ackerman and Okubo (1993). Since turbulence depends on the current velocity and the structure of the SAV bed (Koch and Gust 1999), at low current velocities the turbulence levels are expected to be low. As the current velocity increases, turbulence levels also increase. At the point where the vegetation begins to bend over due to the current velocity, the water flow is redirected over the vegetation and turbulence levels among the plants may decrease again (Nepf *et al.* 1997).

Since mass transport of nutrients and carbon in SAV beds depends on turbulence levels, it can be predicted that SAV can benefit from turbulence in the water. The optimal turbulence levels for SAV is yet unknown. What is known is that SAV beds rescale turbulent energy from larger to smaller eddies. This process depends on the architecture of the SAV bed (Koch 1996; Koch and Gust 1999). Epiphytes colonizing SAV blades decrease the distance between "obstructions to the flow" (like blades and shoots) and rescale turbulence to even smaller eddies than those found among blades without epiphytic growth (Koch 1994, 1996).

Rescaling of turbulence occurs at the individual plant level (Anderson and Charters 1982) and at the canopy level (Gambi *et al.* 1990; Koch 1996) and may be a mechanism for creating mixing lengths of biological importance (i.e., mixing of the water that results in increased productivity). Until turbulence in SAV beds is better understood, few predictions regarding the importance of turbulence for the health and distribution of SAV can be made.

SAV AND TIDES

Most SAV species are not tolerant of dessication because they lack the waxy cuticle found in terrestrial plants and, thus cannot grow in the intertidal zone. Small SAV species that are found in intertidal pools (like plants from the genus *Halophila*) and SAV beds that retain water between their leaves at low tide, can colonize the intertidal area. These are the exceptions. Additionally, plants that colonize the intertidal area in temperate zones often are removed by shifting ice during the winter. Consequently, the minimum depth of distribution of most SAV species is limited to the mean low water level while the maximum depth of distribution is limited by the light availability (Figure VI-4).

As mentioned above, waves may also limit the minimum depth of SAV distribution (see Figure VI-2), therefore, tides and waves need to be considered as confounding factors when analyzing the vertical distribution of SAV. As waves and tides co-occur in many SAV habitats, tides will constantly change the wave mixing depth (see above). Therefore, theoretically, the minimum depth of distribution should be at a depth below the mean low water (MLW) line–the MLW level plus the wave mixing depth (Figure VI-5).

Minimum Depth of Distribution

The minimum depth of distribution based on tides alone can be defined as half the tidal amplitude (A in m) below mean tide level (MTL) (see Figure VI-4). In areas with diurnal tidal cycles, this will be {MHW-

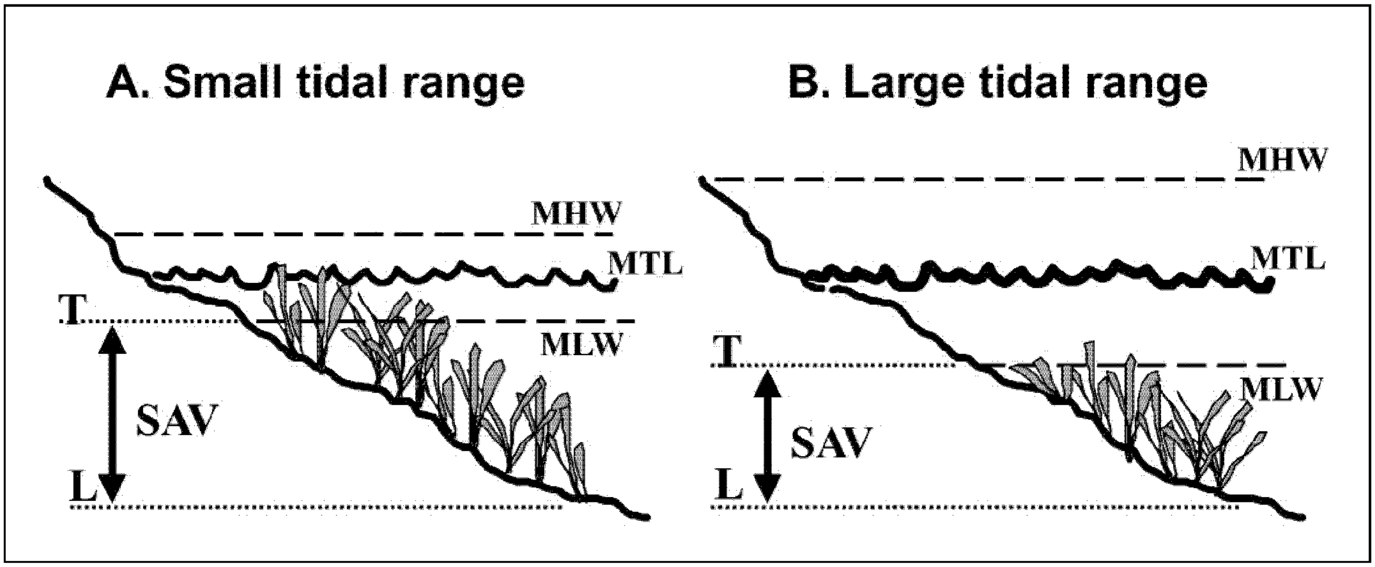

FIGURE VI-4. Tidal Range Influence on Vertical SAV Depth Distribution. The vertical range of distribution of SAV beds can be reduced with increased tidal range. The minimum depth of SAV distribution (Z_{min}) is limited by the low tide (T), while the maximum depth of SAV distribution (Z_{max}) is limited by light (L). The SAV fringe (arrow) decreases as tidal range increases. A small tidal range results in a large SAV depth distribution (A), whereas a large tidal range results in a small SAV depth distribution (B). Mean high water (MHW), mean tide level (MTL) and mean low water (MLW) are all illustrated.

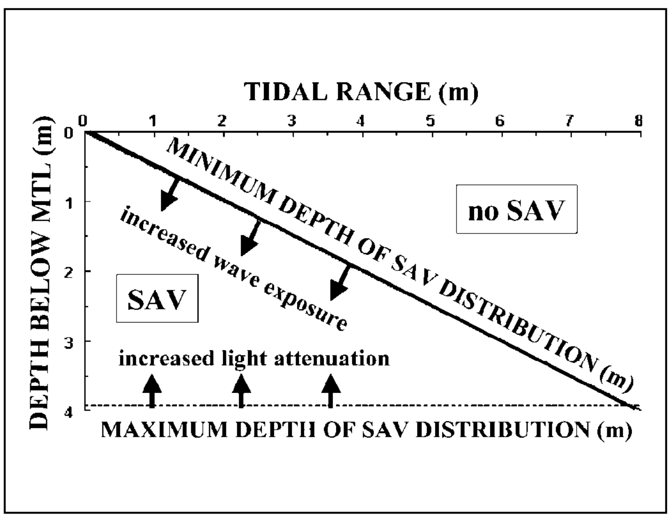

FIGURE VI-5. Minimum and Maximum Depth of SAV Distributions as a Function of Tidal Range. The minimum depth of SAV distribution defined as the mean low water (MLW) line decreases with wave exposure (see Figure VI-2), while the maximum depth of SAV distribution decreases with increasing light attenuation coefficients. MTL is the mean tide level.

MLW}/2, while in areas with semi-diurnal tides it will be {MHHW-MLLW}/2, where MHW is mean high water, MHHW is mean higher high water and MLLW is mean lower low water. A method to calculate the minimum depth of distribution (Z_{min}) including the wave mixing depth has been suggested by Chambers (1987) and is described above. It should theoretically be defined as:

$$Z_{min} = \frac{A}{2} + \frac{\frac{gT^2}{2\pi}}{2} \qquad \text{(VI-4)}$$

where the first term of the equation refers to the tidal amplitude and the second term refers to the wave mixing depth (see Equation VI-2). Equation VI-4 suggests that in areas of high tidal amplitude and high wave exposure, SAV will be forced to colonize relatively deep waters. Its success in colonizing such areas will depend on their maximum depth of distribution.

Maximum and Vertical Distributions

The maximum depth of distribution of SAV depends on the light attenuation in the water column (K_d) as well as on the water depth (which is a function of tides). Therefore, tides and the maximum depth of distribution of SAV are confounding factors (Carter and Rybicki 1990; Koch and Beer 1996). In areas with high tidal amplitude: 1) SAV is forced into deeper areas due to dessication and freezing (Figure VI-4); and 2) the water column is deeper during high tide than in an area with a smaller tidal amplitude (i.e., there is more water to attenuate light). This will reduce the light available to the plants as well as the number of hours of saturating light levels (Koch and Beer 1996). Therefore, the SAV bed is limited by the upper (determined by tides and waves) and lower (determined by light penetration) depths of distribution (Figure VI-5).

The maximum depth of distribution (Z_{max}) can be calculated based on the Lambert-Beer equation:

$$Z_{max} = \frac{-\ln\left(\frac{I_z}{I_o}\right)}{K_d} \qquad \text{(VI-5)}$$

where I_z / I_o is the percent light required by the species under consideration or the percent light at the maximum depth of distribution of the plants. From Equation VI-5, it is evident that, as K_d increases, the maximum depth of distribution becomes shallower, which further restricts the vertical distribution of the plants (Figure VI-6).

No SAV species can survive if

$$Z_{max} \leq Z_{min} \qquad \text{(VI-6).}$$

This shifts the focus from considering how deep SAV can grow to how narrow their depth distribution can be in order to sustain healthy beds. For *Z. marina* to successfully colonize an area in Long Island Sound, Koch and Beer (1996) found that

$$Z_{max} \geq 1\text{m} + Z_{min} \qquad \text{(VI-7)}$$

was a necessary condition for the existence of this SAV species. This 1-meter potential vertical depth distribution below Z_{min} is necessary as a buffer when, during storm events, the shallower portion of the SAV bed is exposed to air, rain or ice. The deeper portions of this fringe can provide the necessary energy to allow the shallower portion to recover from the stress of exposure (Koch and Beer 1996).

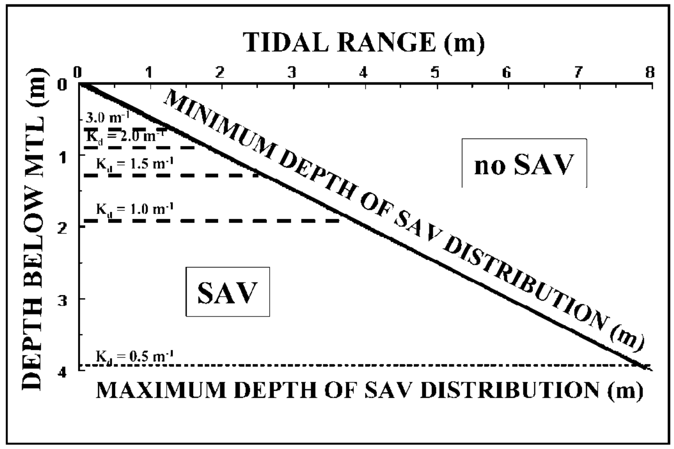

FIGURE VI-6. Effect of Increased Light Attenuation on Maximum Depth of SAV Distribution. The magnitude of the effect of increased light attenuation (K_d) on the maximum depth of SAV distribution as determined based on the equations presented in the text, assuming a SAV minimum light requirement of 13 percent. MTL is the mean tide level.

For the mixture of estuarine species in Chesapeake Bay, the vertical depth of distribution seems to be smaller than that found for Long Island Sound, but this value still needs to be defined.

The management implication of not only considering the maximum depth of distribution for SAV but the vertical depth range that they can colonize is that, in areas with high tidal ranges, testing attainment of minimum light requirements needs to be adjusted to account for tidal ranges. The reason for this is that if the tidal range is large (i.e., Z_{min} is relatively deep) and the light availability is low (i.e., Z_{max} is relatively shallow), SAV may be restricted to such a narrow vertical depth that its long-term survival is not viable (Koch and Beer 1996).

Figure VI-7 indicates how K_d in combination with tidal range and depth can be used to predict the vertical distribution of SAV in an area. In Figure VI-7, a tidal range of 0.8 meters (see x-axis), a minimum light requirement of 14 percent (I_z/I_o) and a K_d=1.5 m^{-1} (see horizontal dashed lines) are assumed. A line is drawn vertically from the 0.8-meter tidal range. The depth at which it intersects the diagonal line determines Z_{min} while the depth at which it intersects the horizontal dashed line for the selected K_d value

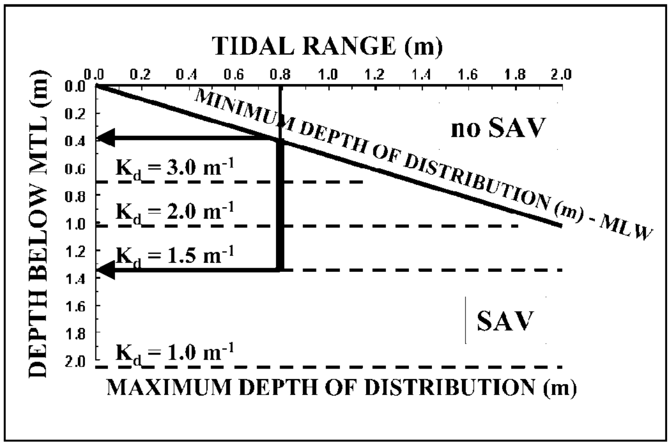

FIGURE VI-7. Area-Specific Prediction of Vertical SAV Depth Distribution. An example of how this type of graph can be used to predict the vertical distribution of SAV in a certain area. A tidal range of 0.8 m (see x-axis), a minimum light requirement of 13 percent (part of the equation to determine Z_{max}) and a K_d = 1.5 m^{-1} (see horizontal dashed lines) are assumed. A line is drawn vertically from the 0.8 m tidal range. The depth at which it intersects the diagonal line determines Z_{min} while the depth at which it intersects the horizontal dashed line for the selected K_d value determines Z_{max}. In this case, SAV has the potential to grow in a fringe between 0.4 and 1.3 m deep. MTL is the mean tide level.

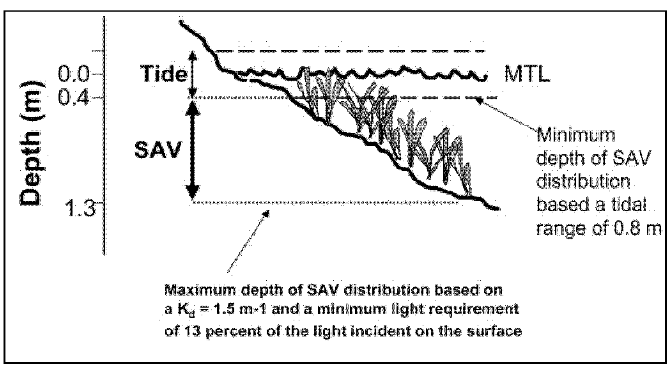

FIGURE VI-8. Illustration of Tidal Range Influences on Vertical SAV Depth Distribution. Illustration of the SAV vertical depth distribution fringe determined in Figure VI-7. The fringe will occur in a 0.9 m depth interval (1.3-0.4 m) due to tidal limitations at the top and light limitations at the bottom.

determines Z_{max}. In this case, SAV has the potential to grow in a fringe between 0.4 and 1.3 m depth (vertical bar in Figure VI-7 and SAV arrow in Figure VI-8) . In this case, the SAV fringe will be 0.9 meters deep (1.3 meters–0.4 meters).

Tidal amplitudes in Chesapeake Bay (MHHW-MLLW) range from nontidal in some dammed tributaries to 50 cm in the upper Potomac River, Washington, DC, 60 cm in the Patuxent River, Maryland and 64 cm in the Nansemond River, Virginia. SAV light requirements of K_d 1.5 and 2 m^{-1} were established in 1992 for Chesapeake Bay, based on a 1-meter restoration depth (Batiuk *et al.* 1992). With this relatively high light attenuation, SAV would probably not exist if tidal ranges were higher than 1 meter (this allows SAV to colonize a fringe between 75 and 40 cm in depth, respectively). From Figure VI-9a, it can be seen that, when the low tide at the Nansemond River occurs at noon, the maximum light intensity resembles that of full sunlight but, the hours of saturating light (H_{sat}) decrease with increasing K_d. Figure VI-9b shows the dramatic effect that a high tide at noon has on the light availability to SAV in the Nansemond River. The higher the K_d, the less light is available to the SAV when the high tide is at noon. Figures VI-9a and VI-9b are based on a clear sunny day. If the day is cloudy, the effect of a high tide at noon could lead the SAV to be exposed to light levels below saturation while a low tide at noon could reduce the number of hours of saturating light that the plants receives even on a sunny day by reducing the light available to the plants in the early morning and late afternoon (high tides).

Tides have a significant effect on the light available to SAV in Chesapeake Bay, where tidal amplitudes are relatively small but K_d values are relatively high. In areas with lower K_d values in the past, an increase in K_d, combined with high tidal amplitudes, can jointly contribute to the decline of SAV distribution (Koch and Beer 1996).

The SAV light requirements presented in the first SAV technical synthesis (Batiuk *et al.* 1992) were established based on a restoration depth of 1 meter MLW (mean low water) without considering tidal range levels. This overestimated Z_{max} and underestimated the water quality necessary to allow SAV to recolonize areas down to a depth of 1 meter (Z_{max} = 1 meter).

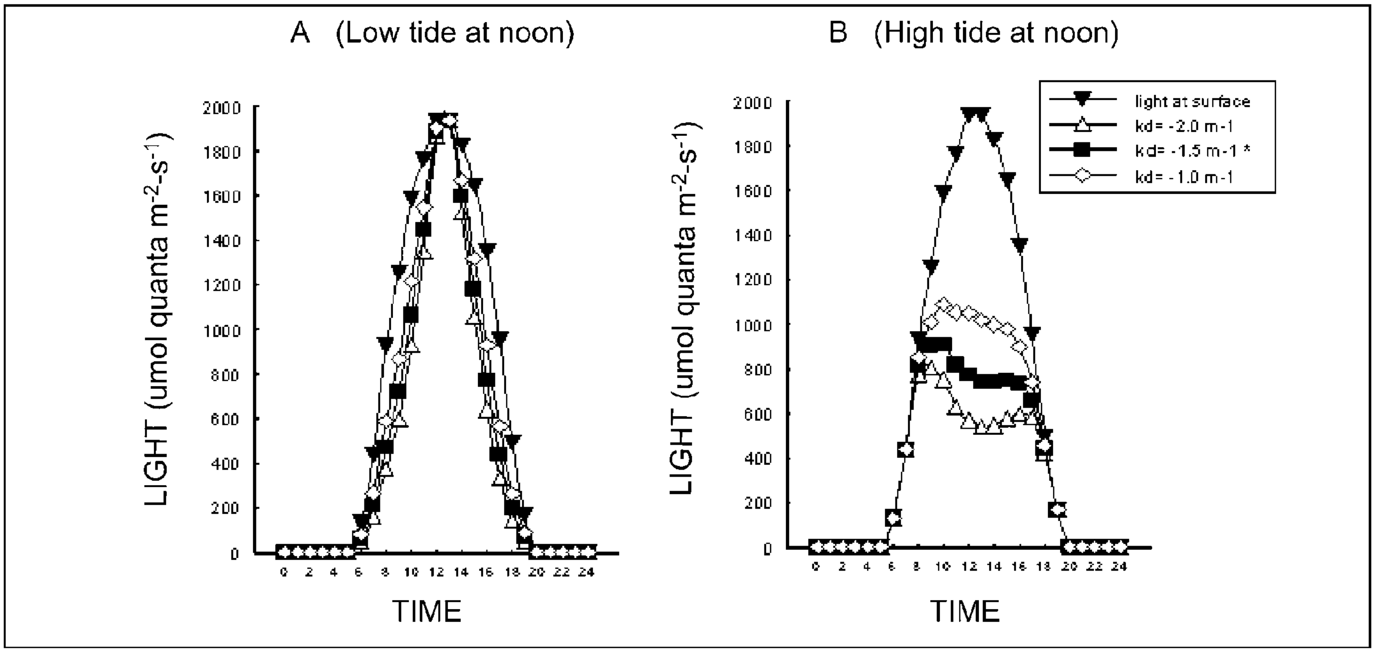

FIGURE VI-9. Simulated Diurnal Light Curves for Different Light Attenuation Coefficients. Simulated diurnal light curves for different light attenuation coefficients (K_d) in the Nansemond River, Virginia, with a 64 cm tidal range during a clear, cloudless day, when the low tide occurs at noon (A) and when the high tide occurs at noon (B). The horizontal line indicates the light level that saturates photosynthesis. The number of hours of saturating light (H_{sat}) decrease with increasing K_d values when low tide occurs at noon (A) Although the number of hours of saturating light are not affected when high tide occurs at noon (B), the higher the K_d, the lower the light levels available to the SAV (B).

Table VI-4 summarizes the differences between the 1992 SAV light requirements based on MLW and the revised light requirements taking the tidal amplitudes into account. These values were obtained by changing Z in Lambert-Beer's equation to Z + A/2, where A is the tidal amplitude:

$$K_d = \frac{-\ln(\frac{I_z}{I_o})}{Z + \frac{A}{2}} \qquad \text{(VI-8).}$$

In summary, tidal amplitude and K_d have a strong confounding effect on the distribution of SAV. This has been conclusively demonstrated in the literature, and simple equations exist to predict the SAV distribution based on the interaction between tides and K_d (Koch and Beer 1996). In order to incorporate tidal amplitude as an SAV habitat requirement in Chesapeake Bay, it is necessary to determine the minimum vertical distribution for marine, estuarine and freshwater SAV species. From Figure VI-7, it can be concluded that SAV will not occur in areas where K_d=2 m^{-1} if the tidal range is equal or higher than 1.8 meters. Under these conditions $Z_{max}=Z_{min}$. The true tidal requirement can only be determined once the minimum fringe of distribution for the SAV species in question is determined.

SAV AND THE SEDIMENTS IT COLONIZES

Sediments are important in determining the growth, morphology and distribution of SAV (Short 1987; Livingston *et al.* 1998) due to the availability of nutrients and phytotoxins as well as erosional/deposition processes (Marba *et al.* 1994; Dan *et al.* 1998; Koch 1999). Extreme events causing massive erosion or deposition of sediments can cause the death of entire SAV populations. The sediment underlying an SAV bed in Florida was completely eroded away and redeposited elsewhere (Hine *et al.* 1987). The massive destabilization of this population may have been caused by heavy grazing of the plants.

TABLE VI-4. Light attenuation requirements necessary for the recovery of SAV down to the 1 meter depth contour, taking tides into account. I_z/I_o (PLW) is assumed to be 13 percent for tidal fresh and oligohaline plants and 22 percent for mesohaline and polyhaline plants.

Salinity Regime	Mean Tidal Range	SAV K_d (m^{-1}) habitat requirement for 1 m restoration target[1] based on MLW[2] + tidal range
	0.0 m	1.97
Tidal fresh	0.1 m	1.87
and	0.2 m	1.79
oligohaline	0.3 m	1.71
	0.4 m	1.64
	0.5 m	1.57
	0.6 m	1.51
	0.0 m	1.51
Mesohaline	0.1 m	1.44
and	0.2 m	1.37
polyhaline	0.3 m	1.32
	0.4 m	1.26
	0.5 m	1.21
	0.6 m	1.16

SAV habitat requirements from Batiuk *et al.* 1992.
Mean low water.

On the other extreme, high sedimentation rates can also be responsible for the decline of SAV populations. Moderate depositional rates can stimulate the growth of *Thalassia testudinum* (Gallegos *et al.* 1993) and *Cymodocea nodosa* (Marba and Duarte 1994), but high depositional rates can lead to the disappearance of these plants.

Seedlings are more susceptible to high burial rates than established SAV beds (Marba and Duarte 1994). Therefore, the season of depositional events is important in determining the chances of survival of SAV beds. The deposition of more than 10 cm of sediment on top of *V. americana* tubers reduced their chances of becoming mature plants and establishing a meadow (Rybicki and Carter 1986). Such high depositional rates can occur during severe storms. In contrast, *Z. marina* seeds need to be buried at least 0.5 cm, where conditions are anoxic, to promote germination (Moore *et al.* 1993).

During less extreme conditions, SAV can modify the characteristics of the sediment it colonizes by reducing current velocity and attenuating waves within its beds (see the review by Fonseca, 1996). This leads to the deposition of small inorganic and light organic particles (Kenworthy *et al.* 1982). The suitability of fine sediments and sediments with high organic content for SAV growth are addressed below.

Grain Size Distribution

Sediments within SAV beds are finer than those in adjacent unvegetated areas (Scoffin 1970; Wanless 1981; Almasi *et al.* 1987). As SAV density increases, the ability to accumulate fine particles is also enhanced (due to the reduction in current velocity and wave energy). As grain size distribution becomes skewed toward silt and clay, the porewater exchange with the overlying water column decreases. This may result in increased nutrient concentrations (Kenworthy *et al.* 1982) and phytotoxins such as sulfide in marine sediments (Holmer and Nielsen 1997). At the other extreme, if SAV colonizes coarse sand, the exchange of porewater with the overlying water column will be enhanced and nutrient availability in the sediment may be lower than that of finer sediments.

In an experiment using different grain sizes of ground glass (to avoid adsorbed nutrients), *Ruppia maritima* was found capable of colonizing sediments from a silt/clay mixture to coarse sand. Maximum growth was observed in fine and medium sand particles (Seeliger and Koch, unpublished data).

Table VI-5 lists quantitative and qualitative data on the silt and clay amount found in healthy SAV beds. The values range from 0.4 to 90.1 percent. The highest values seem to be associated with beds in lower salinity environments with the exception of a *Zostera muelleri* bed. Perhaps, in such environments, the plants are able to colonize sediment with reduced porewater exchange with the water column because sulfide does not occur at the same levels as in marine/higher salinity estuarine systems. In higher salinity environments, it appears that plants need sediments that are more oxygenated and in which sulfide levels can be reduced via higher porewater advection rates. Therefore, SAV growth may be limited by the physical and

TABLE VI-5. Percent fine sediment (< 63 μm) or sediment type found in healthy SAV beds[1]

Percent fines/sediment type	Species	Source
1.9	*Syringodium filiforme*	Wood *et al.* 1969
4.8	*Thalassia testudinum*	Wood *et al.* 1969
0.4 - 9.0	*Posidonia oceanica*	Edgar and Shaw 1995
1.8 - 9.2	*T. testudinum, S. filiforme* and *Halodule wrightii*	Livingston *et al.* 1998
6 -10	Chesapeake Bay SAV	Batiuk *et al.* 1992
14	*Zostera marina*	Marshall and Lucas 1970
14.6	*T. testudinum*	Scoffin 1970
0.8 - 14.7	*Thalassia* and *Halodule*	Grady 1981
15	*Z. marina*	Orth 1977
8.1 - 28.8	*Halodule* and *Zostera*	Murphey and Fonseca 1995
2.8 - 30.9	*Heterozostera tasmanica*	Edgar and Shaw 1995
1 - 34	*T. testudinum*	Burrell and Schubel 1977
2 - 39 % clay	Tidal Potomac River SAV	Carter *et al.* 1985
40	*Hydrilla* and *Vallisneria*	Posey *et al.* 1993
4.3 - 47	No SAV (*Thalassia, Syringodium* and *Halodule*)	Livingston *et al.* 1998
58	*Hydrilla verticillata*	Posey *et al.* 1993
4 - 62 % silt	Tidal Potomac SAV	Carter *et al.* 1985
48 % silt and 14% clay	*Vallisneria americana*	Hutchinson 1975
0.5 - 72	*Zostera muelleri*	Edgar and Shaw 1995
4.7-90.1	Mixture of *Vallisneria, Potamogeton perfoliatus, P. pectinatus, Ruppia maritima*	Pascal *et al.* 1982
"Silt loving"	*P. pectinatus*	Sculthrope 1967; Haslam 1978
Silty substrate	*P. perfoliatus*	Haslam 1978

[1]Arranged in ascending order of maximum percentage of fine sediments.

continued

TABLE VI-5. Percent fine sediment (< 63 μm) or sediment type found in healthy SAV beds[1] (*continued*)

Percent fines/sediment type	Species	Source
Silty substrate	*Sagittaria sagittifolia*	Haslam 1978
Mud	*Ceratophyllum demersus*	Hutchinson 1975
Organic ooze	*Myriophyllum spicatum*	Patten 1956
Soft or sandy mud	*Myriophyllum spicatum*	Springer 1959
Muds or sand	*Ruppia maritima*	Anderson 1972
Clay and sand	*Zannichellia palustris*	Stevenson and Confer 1978
Medium-grained substrate	*Myriophyllum spicatum*	Haslam 1978
Medium-grained substrate	*Ranunculus*	Haslam 1978
Sandy	*Najas guadalupenses*	Martin and Uhler 1939

[1]Arranged in ascending order of maximum percentage of fine sediments.

geochemical processes associated with a certain sediment type and not by the grain size per se (Barko and Smart 1986). Data in Table VI-5 are not sufficient to establish the 'best' sediment types for SAV growth at this time.

Sediment Organic Content

SAV tends to accumulate organic particles due to a reduction in current velocity and wave energy within the meadows and canopies. Organic matter can also be accumulated in SAV colonized sediments through the burial of rhizomes and roots produced over time. The age of the organic deposits beneath a *Posidonia oceanica* bed were found to be up to 3,370 years old (Mateo *et al.* 1997). High burial rates and/or low decomposition rates may account for the accumulation of organic matter over such long periods.

The organic carbon content of sediments from the mainstem Chesapeake Bay has increased two to three times over the last 80-100 years (Cornwell *et al.* 1996). This was attributed to changes in inorganic matter deposition due to increased phytoplankton biomass (Harding and Perry 1997) as well as time-dependent changes in organic matter decomposition. If the organic content of the sediments in shallow areas in Chesapeake Bay SAV habitats are also increasing, they could limit the distribution of SAV. Barko and Smart (1983) and Koch (unpublished data) concluded that the growth of SAV is limited to sediments containing less than 5 percent (dry weight) organic matter. This is also supported by other data summarized in Table VI-6.

The mechanism behind this limitation of high sediment organic content on SAV growth is not well understood. It may be due to nutrient limitation in very fine sediments associated with high organic deposits (Barko and Smart 1986) or due to high sulfide concentrations in marine sediments, known to be toxic to high salinity SAV (Carlson *et al.* 1994).

The data in Table VI-6 lists organic contents of less than 12 percent for SAV colonized sediments. The higher values (6.5 to 12 percent) are mostly associated with SAV species that have large leaves. Perhaps these

TABLE VI-6. Sediment organic matter as percent of dry weight in healthy SAV beds.[1]

Percent Organics	Species	Source
1.25	*Zostera marina*	Marshall and Lukas 1970
1.25	*Z. marina*	Orth 1977
0.41 - 1.38	*Z. marina*	Dan *et al.* 1998
<2	*Ruppia maritima*	Ward *et al.* 1984
2.5	*Syringodium filiforme*	Wood *et al.* 1969
3.25	*R. maritima*	Kemp *et al.* 1984
0.77 - 3.62	*Halodule* and *Zostera*	Murphey and Fonseca 1995
3.5 - 4.9	*Thalassia testudinum*	Wood *et al.* 1969
< 5	*Z. marina*	Koch 1999
< 5	*Hydrilla* and *Potamogeton nodosus*	Barko and Smart 1983
1 - 5.3	Chesapeake Bay SAV	Batiuk *et al.* 1992
2.6 - 5.3	*Heterozostera tasmanica*	Edgar and Shaw 1995
< 6.5	*Vallisneria americana*	Hutchinson 1975
0.8 - 7.3	*Zostera muelleri*	Edgar and Shaw 1995
8	*Z. marina*	Short (personal communication)
1.6 - 12	*Posidonia spp.*	Edgar and Shaw 1995
< 26 mg C g^{-1}	*Potamogeton pectinatus*	van Wijk *et al.* 1992

[1] Arranged in ascending order of maximum percentage of organic matter.

plants can colonize sediments with higher organic content due to a large oxygen production in the leaves and, consequently, also a higher transport of oxygen to the roots. If the rhizosphere is well-oxygenated, the detrimental effects associated with high organic content in the sediments may be neutralized. The distribution of *Potamogeton spp.* in English Lakes (Pearsall 1920; summarized in Hutchinson 1975) was directly correlated with sediment organic content (X) and minimum light requirement (Y) where $Y=0.70 + 0.65\ X$ ($r^2=0.90$). Therefore, plants growing in more organic sediments with higher concentrations of phytotoxic metabolites require more light to support greater release of oxygen from their roots to the rhizosphere. This mechanism has been used to explain the decline in abundance of SAV populations in eutrophic regions that have experienced an increase in sediment organic content (Nienhuis, 1983).

Due to the large numbers of studies that observed the percent organic matter in SAV beds to be below

5 percent, it is recommended that caution should be taken when transplanting SAV into areas where the sediment organic content is higher than that value. Additional studies are needed to define the SAV habitat requirement for organic matter for different SAV species in Chesapeake Bay.

SAV AND SEDIMENT GEOCHEMISTRY

Nutrients in Sediments

Nutrients in the sediment can be limiting to the growth of SAV (Short 1987; Agawin *et al.* 1996) but do not seem to eliminate it from colonizing certain areas. In marine siliceous sediments, nitrogen may limit SAV growth (Short 1987; Alcoverro *et al.* 1997) while in marine carbonate sediments, phosphorus may be limiting to SAV growth (Wigand and Stevenson 1994). Potassium has been suggested to be limiting to the growth of freshwater SAV (Anderson and Kalf 1988). Mycorrhizae have been found to facilitate the phosphorus assimilation in *V. americana* (Wigand and Stevenson 1997), but little or no information is available on mycorrhizae in the rhizosphere of marine SAV (Wigand and Stevenson 1994).

Although light seems to be more limiting to SAV growth than sediment nutrient concentrations, exceptions can be found. In tropical SAV beds, light and temperature are limiting in the winter while nutrients are limiting in the summer (Alcoverro *et al.* 1997b). Additionally, ammonium concentrations as low as 25 μm (in the seawater) can be toxic to *Z. marina* and ultimately lead to its decimation (van Katwijk *et al.* 1997).

Microbial-Based Phytotoxins

A wide variety of potentially phytotoxic substances is produced by bacterial metabolism in anaerobic sediments, including phenols and organic acids, reduced iron and manganese and hydrogen sulfide (Yoshida 1975; Gambrell and Patrick 1978). In many aquatic environments, sulfide probably constitutes the most important of these toxic bacterial metabolites and has been shown to be toxic to estuarine and marine SAV species (van Wijck *et al.* 1992; Carlson *et al.* 1994).

Sulfide is generated by sulfate reducing bacteria during organic carbon oxidation and nutrient remineralization in anoxic sediments (Howarth 1984; Pollard and Moriarty 1991). A high remineralization rate leads to high nutrient availability and favors plant growth but can also lead to the accumulation of sulfide, which is detrimental to plant growth. Sulfate remineralization depends on the temperature and amount of organic matter in the sediment. In freshwater sediments, sulfate reduction is less important than methanogenesis due to the lower sulfate availability. As SAV tends to accumulate more organic and inorganic particles than unvegetated areas, sulfate reduction rates can be expected to be higher within the vegetation than outside it (Isaksen and Finster 1996; Holmer and Nielsen 1997). This difference could also be due to the excretion of organic compounds through the roots (Blackburn *et al.* 1994).

Table VI-7 summarizes sulfide levels observed in healthy as well as deteriorating SAV beds, and Table VI-8 lists sulfate reduction rates in healthy SAV beds. While eutrophication can fuel sulfide production via increased organic matter in the sediments, sulfide production can also fuel eutrophication. The sulfide produced inhibits nitrification ($NH_4^+ \rightarrow NO_3^-$) and, consequently, increases ammonium fluxes to the water column, which could act as a positive feedback to eutrophication (Joye and Hollibaugh 1995).

A parallel mechanism also applies to the release of phosphorus from the sediments. When sulfides react with iron in the sediment, iron sulfide is formed and phosphorus is released (Lamers *et al.* 1998). If the phosphorus is not taken up by the plants, it may be released back into the water column and, as stated above for nitrogen, may be a positive feedback to eutrophication.

The toxicity of sulfide to plants can also be enhanced by eutrophication. Oxygen released from SAV roots is needed to oxidize the sulfide and reduce its toxic effects (Armstrong 1978). The release of oxygen by the roots depends on the photosynthetic rates of the plant. Therefore, if eutrophication leads to a reduction in light availability, photosynthetic rates will be lower, the amount of oxygen released from the roots will also be reduced and sulfide toxicity may be enhanced (Goodman *et al.* 1995).

TABLE VI-7. Sulfide levels in the sediments of healthy and dying SAV beds.

Sulfide concentration [1]	Species	Plant Status	Source
350 to 1,000 μM	*Thalassia testudinum*	Healthy	Carlson *et al.* 1994
88 m mol m^{-2} AVS	*Halodule beaudetti*	Healthy	Blackburn *et al.* 1994
< 0.2 mM H_2S	*Halophila engelmanii*	Growth	Pulich 1983
0.48 to 1.27 mg g^{-1}	*Potamogeton pectinatus*	Declining growth	van Wijck *et al.* 1992
> 400 μM	*Zostera marina*	Reduced photosynthesis	Goodman *et al.* 1995
> 2,000 μM	*T. testudinum*	Dead	Carlson *et al.* 1994

[1]Note the different units.

TABLE VI-8. Sulfate reduction in healthy SAV beds.

Sulfate reduction [1]	Species	Source
20 n mol ml^{-1} h^{-1}	*Zostera noltii*	Welsh *et al.* 1996
87 to 445 n mol cm^{-3} d^{-1}	*Z. noltii*	Isaksen and Finster 1996
7 to 7.9 m mol m^{-2} d^{-1}	*Syringodium isoetifolius*	Perry and Dennison submitted
9.4 m mol m^{-2} d^{-1}	*Halophila*	Perry and Dennison submitted
9.5 to 11.7 m mol m^{-2} d^{-1}	*Zostera capricorni*	Perry and Dennison submitted
12 to 16.8 m mol m^{-2} d^{-1}	*Halodule uninervis*	Perry and Dennison submitted
16.3 m mol m^{-2} d^{-1}	*Halodule beaudetti*	Blackburn *et al.* 1994
27.9 to 33.4 m mol m^{-2} d^{-1}	*Cymodocea serrulata*	Perry and Dennison submitted
59.1 m mol m^{-2} d^{-1}	*Zostera marina*	Holmer and Nielsen 1997

[1]Note the different units.

Sulfide concentration in the sediment is an important SAV habitat requirement. Correlations between pore-water sulfide concentrations and the growth of several SAV species have indicated that concentrations above 1 mM may be toxic (Pulich 1989; Carlson *et al.* 1994). Direct manipulations of sulfide concentrations revealed a negative effect on photosynthesis (Goodman *et al.* 1995) and growth (Kuhn 1992) when levels were higher than 1 to 2 mM. Sulfide thresholds for different SAV species (in combination with different light levels) still need to be determined. Until such data are available, critical sulfide concentrations cannot be specified as an SAV habitat requirement.

CHEMICAL CONTAMINANTS

This review is intentionally confined to the broad issues of the potential roles contaminants may have in limiting the size, density and distribution of SAV populations. Literature values pertaining to the relationships between SAV and chemical contaminants are derived from three diverse lines of inquiry: contaminant studies, phytoremediation efforts (Garg *et al.* 1997; Peterson *et al.* 1996; Ramanathan and Burks 1996; Salt *et al.* 1995), and recommendations for aquatic weed control (Anderson and Dechoretz 1982; Anderson 1989; Nilson and Klaassen 1988). Appendix B summarizes some of the more recent work devoted to contaminant issues.

Most of the chemical contaminant studies have evaluated the effects of herbicides on SAV growth (Fleming *et al.* 1993). A few have examined other pesticides or heavy metals (Garg *et al.* 1997; Gupta and Chandra 1994; Gupta *et al.* 1995). Thus, the vast majority of compounds known to have toxic effects on biological systems remain untested (Van Wijngaarden *et al.* 1996) and only a few efforts have been made to systematically evaluate additive, cumulative and synergistic effects of multiple contaminants (Fairchild *et al.* 1994; Huebert and Shay 1992; Sprenger and McIntosh 1989).

Nonetheless, the following conclusions can be drawn from these accumulated data.

- Herbicides have been shown to be phytotoxic to SAV. Toxicity is somewhat species-dependent and chemical-specific. Table VI-9 depicts the toxicity range of the most widely used herbicides in the

TABLE VI-9. Relative effects of herbicides on net photosynthesis in *Potamogeton pectinatus*. The IC_{50} is the predicted concentration that inhibits photosynthesis by 50%. Photosynthesis was determined by measuring O_2 production by plants over 3 hours at 20-22°C and about 58% μmol/m^2/sec of photosynthetically active radiation from full spectrum fluorescent lighting. Plants were exposed to herbicides added to the water column. Reprinted with permission: W. James Fleming 1993.

Herbicide	Range of Concentration Tested (ppb)	N	IC_{50} (ppb)	95% Confidence Interval	Slope	R^2
Acifluorfen	1,000 - 10,000		>10,000			
Alachlor	1,000 - 10,000		>1,000;<10,000			
Atrazine	30 - 2,000	30	29	20 - 42	-50.97	0.81
Cyanazine	5 - 3,125	25	32	21 - 48	-42.91	0.88
Glyphosate	1,000 - 10,000		>10,000			
Linuron	20 - 1,950	36	70	43 - 112	-59.14	0.64
Paraquat	8 - 8,000	36	240	130 - 420	-36.04	0.68
Metolachlor	1,000 - 10,000		>10,000			
Metribuzin	4 - 13	30	8	5 - 12	-41.25	0.86
Simazine	30 - 2,680	25	164	82 - 327	-88.80	0.58
2,4-D	1,000 - 10,000		>10,000			

United States on *Potamogeton pectinatus*. Inhibiting concentrations range from 8 ppb to 10,000 ppb. These concentrations are consistent with those observed when aquatic weed control is the management objective, as well as in environments where the protection of aquatic plants is the management objective.

- Pesticides other than herbicides have been shown to have a phytotoxic effect on SAV, although only a few have been evaluated.
- Heavy metals at levels corresponding to some ambient conditions have inhibiting effects on SAV in test systems where the variety of essential plant nutrients has been experimentally factored.
- The environments holding the greatest potential for pesticide suppression of SAV populations are headwaters and shallow waters immediately adjacent to the urban, forest and agricultural areas where pesticides are most widely used and acute concentration level exposures are most likely to occur.
- The environments holding the greatest potential for adverse effects of heavy metals are those where clay and organic sediments chemically concentrate both metals and plant nutrients for extended periods.
- The utility of ambient testing of contaminant concentrations is highly controversial. For pesticides, the constraint of monitoring frequency and location are limiting factors for accurate ambient assessment of contaminant presence. Assessment of heavy metals and other contaminants is confounded by the difficulty of distinguishing between the concentration of biologically active forms and total concentration (Liang and Schoenau 1996).

PHYSICAL AND GEOLOGICAL SAV HABITAT REQUIREMENTS

In order to fully define the SAV habitat requirements in Chesapeake Bay, parameters other than light and its modifiers need to be taken into consideration. Some physical, geological and geochemical parameters have the potential to override established SAV light requirements. Where field and laboratory experimental data were sufficient, physical and geological SAV habitat requirements were identified (Table VI-10).

TABLE VI-10. Summary of physical and geological SAV habitat requirements for Chesapeake Bay.

Parameter	SAV Habitat Requirement	Observations
Current velocity Oligohaline Habitats Polyhaline Habitats	 0 to ? cm s^{-1} >10 and < 100 cm s^{-1}	More data are needed (specially for canopies and meadows; plants with polar/non polar leaves) to further define this SAV habitat requirement.
Minimum depth of SAV distribution	$Z_{\min}=\frac{A}{2}+\frac{\frac{gT^2}{2\pi}}{2}$	A is the tidal amplitude ({MHW-MLW}/2 for diurnal tides and {MHHW-MLLW}/2 for semi-diurnal tides); g is the acceleration of gravity (9.805 m s^{-1}); and T is the wave period.
Maximum depth of SAV distribution	Should be defined by $Z_{\max}=\frac{-\ln(\frac{I_z}{I_o})}{K_d}$	I_z/I_0 is the minimum percent light required by the species under consideration. K_d is the light attenuation coefficient. This calculation should use MWL (mean water level) as a reference. Using MHW (mean high water) may underestimate Z_{max} and using MLW (mean low water) may overestimate Z_{max}.
Tides	SAV can be expected to successfully colonize areas where $Z_{\max}\geq 0.5+Z_{\min}$	0.5 m has been chosen as a conservative value of the smallest vertical depth of colonization observed for SAV in Chesapeake Bay. This value was found to be 1 m for eelgrass in Long Island Sound and needs to be adjusted for the species and sites in question. Z_{min} is the minimum depth of distribution and depends on the tidal range and wave mixing depth (see Equation VI-4).
Sediment grain size Oligohaline Habitats Polyhaline Habitats	 No restrictions? <20% silt and clay	These preliminary SAV habitat requirements are based on compilations of data from the literature. Specific studies are needed to confirm these preliminary requirements.
Sediment organic content	<5%	This SAV habitat requirement is based on a compilation of data from the literature. Although all literature values converge to the suggested value, specific studies are needed to further verify the requirement.

CHAPTER VII

Setting, Applying and Evaluating Minimum Light Requirements for Chesapeake Bay SAV

This chapter defines the two types of minimum light requirements for Chesapeake Bay SAV, and explains how to test their attainment using two new percent-light parameters that can be calculated from water quality monitoring data. It compares the five 1992 habitat requirements from the first SAV technical synthesis (Batiuk *et al.* 1992, Dennison *et al.* 1993) to the new minimum light requirements, in terms of attainment of habitat requirements and their ability to predict SAV presence. The chapter also describes the adjustment of the new percent-light parameters to account for tidal range, and examines the relationships between the two percent-light parameters and the average depth at which SAV is growing in Chesapeake Bay.

DEFINING AND APPLYING THE MINIMUM LIGHT REQUIREMENTS AND WATER-COLUMN LIGHT REQUIREMENTS

Evaluation of ambient water quality conditions supporting the required amount of light reaching SAV can be viewed in terms of two percent-light parameters.

- Percent light through water (PLW) is the amount of ambient sub-surface light absorbed or reflected by water itself, water color caused by dissolved organic materials, suspended organic and sediment particles, and phytoplankton in the water column down to the sediment surface at the restoration depth selected.
- Percent light at the leaf (PLL) is the amount of ambient light that actually reaches the SAV leaf after penetrating the overlying water column and that is further reduced after being absorbed or reflected by epiphytic material growing (attached algae) or settled (organic and inorganic solids) on the SAV leaf surface at the restoration depth selected.

The percent light through water parameter is a component of the percent light at the leaf parameter (Figure VII-1). To reflect these two ways of evaluating percent light, we define a "minimum light requirement" with attainment tested by the percent light at the leaf, or PLL parameter (Table VII-1). We also define a related "water-column light requirement" with attainment tested, as described above, by the percent light through the water or PLW parameter. Note that in the original SAV technical synthesis, published by Batiuk *et al.* (1992), the habitat requirements had the same names as the parameters used to test their attainment, but now they have different names.

The 1992 water quality-based habitat requirements for Chesapeake Bay SAV were applied separately to test their attainment (Batiuk *et al.* 1992). The light attenuation coefficient (K_d) habitat requirement, applied alone, was roughly the equivalent to the water-column light requirement defined here and evaluated by the percent light through the water parameter. Evaluated collectively, the attainment of the five 1992 SAV habitat requirements provided the best estimate at the time for defining the water column conditions necessary to achieve sufficient light at the SAV leaf surface. This estimate is replaced with the attainment of the minimum light requirements defined here.

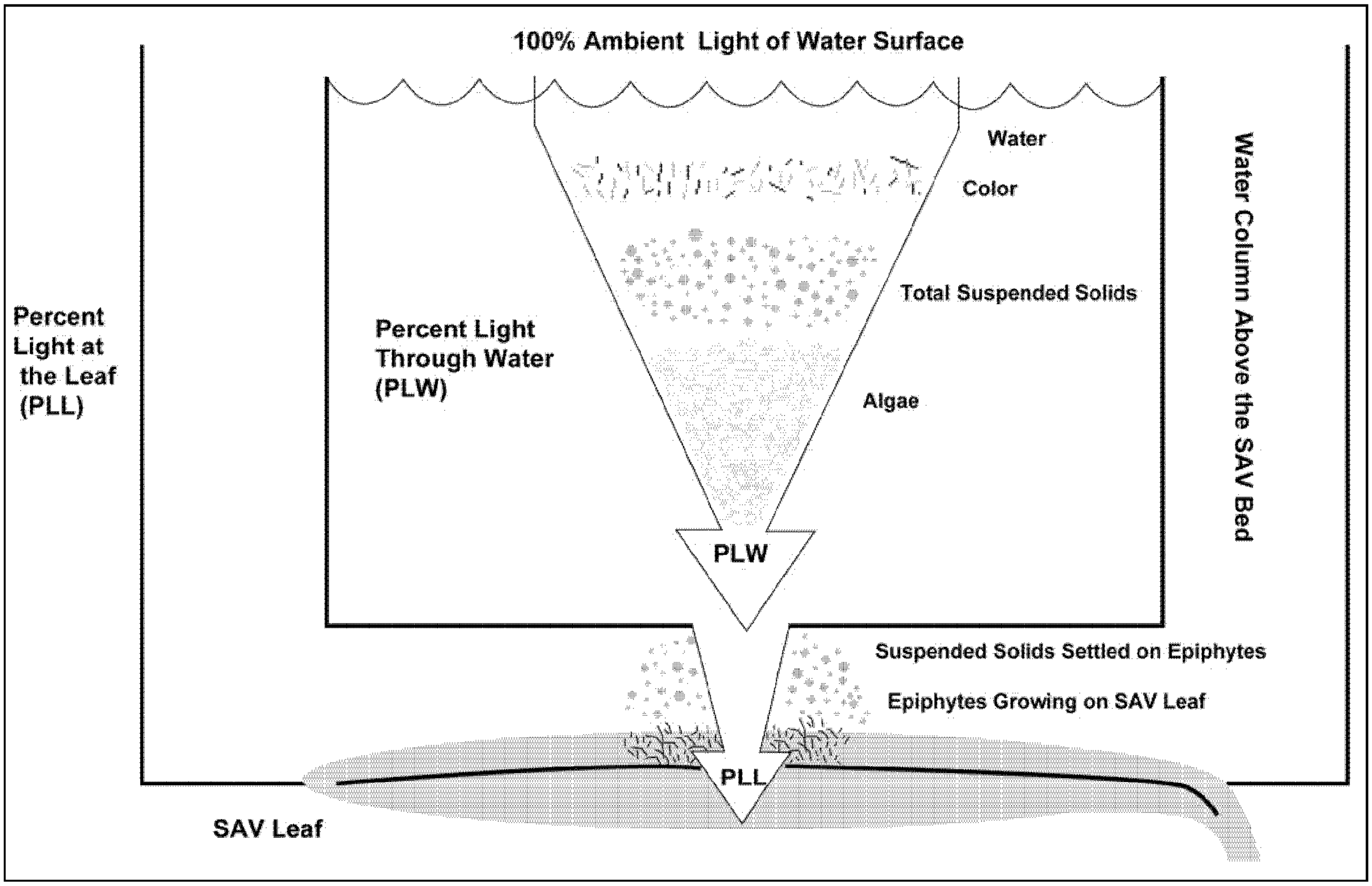

FIGURE VII-1. Two Percent Light Parameters for Evaluating Ambient Conditions. Illustration of the relationship of the two percent light parameters and the water quality conditions influencing both of them.

Water-Column Light Requirements

The water-column light requirements are the same as the two light requirements derived from the in-depth review and analysis of a wide variety of data modeling and research findings documented in Chapter III: 13 percent for tidal fresh and oligohaline areas and 22 percent for mesohaline and polyhaline areas. Since most of the SAV light requirement studies summarized in Chapter III had epiphytes on the SAV, but the light measurements in those studies did not estimate light attenuation due to epiphytes, we used these light requirements to set the water-column light requirements. The attainment of the water-column light requirements is tested using the percent light through the water (PLW) parameter.

Minimum Light Requirements

Minimum light requirements were determined by comparing the results of three lines of evidence.

1. **Calculation using the 1992 SAV habitat requirements.**

One line of evidence was derived by applying the salinity regime-based values for the 1992 SAV habitat requirements for K_d, dissolved inorganic nitrogen, dissolved inorganic phosphorus and total suspended solids (Table VII-1) into the equation for determining PLL (Equation V-1) (Table V-1),

$$PLL=[e^{-(Kd)(Z)}][e^{-(Ke)(Be)}]100.$$

Using this equation, a PLL value of 8.3 percent was calculated for tidal fresh and oligohaline salinity regimes. In mesohaline regimes, the calculated PLL value was 17.3 percent, while it was 13.5 percent in polyhaline regimes. The mesohaline and polyhaline PLL values differed, even though they had the same 1992 K_d and dissolved inorganic nitrogen SAV habitat requirements, because they had different dissolved inorganic phosphorus SAV habitat requirements. This difference influenced

TABLE VII-1. Recommended primary and secondary SAV habitat requirements for Chesapeake Bay and tidal tributaries.

	PRIMARY REQUIREMENTS [1]	SECONDARY REQUIREMENTS [2] (Diagnostic Tools)					
Salinity Regime [3]	**Minimum Light Requirement**	**Water Column Light Requirement [4]**	**Total Suspended Solids (mg/l)**	**Chlorophyll *a*, (μg/l)**	**Dissolved Inorganic Phosphorus (mg/l)**	**Dissolved Inorganic Nitrogen (mg/l)**	**SAV Growing Season [5]**
Tidal fresh	>9%	>13%	<15	<15	<0.02	none	April-October
Oligohaline	>9%	>13%	<15	<15	<0.02	none	April-October
Mesohaline	>15%	>22%	<15	<15	<0.01	<0.15	April-October
Polyhaline	>15%	>22%	<15	<15	<0.02	<0.15	March-May and September.-November

NOTE: All the habitat requirements are independent of restoration depth Z, which is used in calculating percent light at the leaf (PLL) and percent light through water (PLW).

[1] Use the primary requirement, or minimum light requirement, whenever data are available to calculate PLL (which requires light attenuation coefficient [K_d] or Secchi depth, dissolved inorganic nitrogen, dissolved inorganic phosphorus and total suspended solids measurements). The attainment of the minimum light requirement is tested with PLL data to see if an area has water quality that is suitable for SAV growth. There is no equivalent K_d value for PLL, since other parameters are used in calculating it.

[2] The secondary requirements are diagnostic tools used to determine possible reasons for nonattainment of the primary requirement (minimum light requirement) in areas with or without SAV. The water-column light requirement can also be a substitute for the minimum light requirement when data required to calculate PLL are not fully available.

[3] Tidal fresh =<0.5 ppt; oligohaline = 0.5-5 ppt; mesohaline = >5-18 ppt; and polyhaline = >18 ppt.

[4] Use the secondary light requirement, or water-column light requirement, whenever data are not available to calculate PLL, or as a diagnostic tool in conjunction with PLL. Equivalent K_d habitat requirement values can be calculated for different restoration depths Z using $K_d = -\ln(PLW/100)/Z$.

[5] Data used to calculate any of the habitat requirements should be collected during these growing seasons in Chesapeake Bay, or during the local SAV growing season in other estuaries.

Sources for secondary requirements: Batiuk et al. 1992; Dennison et al. 1993.

the limiting nutrient and, therefore, the resulting calculated PLL value. From application of the 1992 SAV habitat requirements, minimum light requirements of 8 percent for tidal fresh/oligohaline regimes and 15 percent (the average of 17.3 and 13.5) were derived from this line of evidence.

2. Accounting for Epiphytic Light Attenuation

As discussed in Chapter III, the scientific studies used to derive the water-column light targets did not factor in the shading effects of epiphytes, which grow on SAV leaves at all depths and on experimentally shaded plants in the field. Several studies in various estuarine habitats indicate that light attenuation by epiphytic communities tends to contribute an additional 15 to 50 percent shading on SAV (e.g., Borum and Wium-Andersen 1980, Bulthuis and Woelkerling 1983, van Dijk 1993). One recent detailed study of turtlegrass beds in Florida coastal waters (Dixon 2000) showed that, while light levels at the maximum depth of seagrass colonization averaged about 22 percent of surface irradiance, epiphytic attenuation reduced this to approximately 14 percent of the surface light that is actually available for plant photosynthesis. This represents an average of approximately 35 percent additional shading by epiphytes.

Light attenuation by epiphytic material appears to be generally important throughout Chesapeake Bay, contributing 20 to 60 percent additional attenuation (beyond PLW) in the tidal fresh and oligohaline regions, where nutrient and total suspended solids concentrations were highest, and 10 to 50 percent in the less turbid mesohaline and polyhaline regions (Figure V-11). These calculated contributions of epiphyte shading are consistent with the values derived for PLW and PLL by applying the 1992 SAV habitat requirement values in equations II-1 and V-1, respectively, where PLL represents approximately 30 percent additional light reduction from PLW (Table VII-1).

Based on literature values for seagrass minimum light requirements, where epiphyte effects were either avoided with experimental manipulation (e.g., Czerny and Dunton 1995) or taken into account with direct measurement (e.g., Dixon 2000), and results from analysis of Chesapeake Bay data, epiphytic material was assumed to make a 30 percent additional contribution to light attenuation throughout Chesapeake Bay shallow water habitats. Accounting for the epiphytic contribution to light attenuation, minimum light requirements for mesohaline/polyhaline and tidal fresh/oligohaline habitats, respectively, were calculated to be 15 percent and 9 percent of surface irradiance. These values, which represent the actual minimum light needed to support SAV growth at the leaf surface, include the additional 30 percent epiphytic light attenuation beyond the respective water-column light targets derived in Chapter III. For mesohaline/polyhaline habitats, factoring the additional 30 percent epiphytic light attenuation into the 22 percent water-column light target yields a 15 percent minimum light requirement as $30\% = 100(22-15)/22$. A 9 percent minimum light requirement for tidal fresh/oligohaline habitats was derived by factoring the additional 30 percent epiphytic light attenuation into the 13 percent water-column light target, as $30\% = 100(13-9)/13$.

The derived SAV water-column light requirement and minimum light requirement for Chesapeake Bay's mesohaline and polyhaline habitats, 22 percent and 15 percent surface light, respectively (Table VII-1), are remarkably close to the respective values of 22 percent and 14 percent surface light derived through field experimentation for turtlegrass in Florida (Dixon 2000) through this second line of evidence.

3. Comparisons of Field Conditions and SAV Growth Gradients

Medians of nearshore water quality data (from the Choptank and York rivers) and Chesapeake Bay Monitoring Program midchannel data were assessed for relationships between calculated PLL values, SAV growth categories and the proposed mesohaline/polyhaline and tidal fresh/oligohaline minimum light requirements of 15 percent and 9 percent, respectively. As described in detail in the section "Comparing Water Quality Medians over Categories of SAV Growth," the calculated PLL values from observed water quality conditions associated with "persistent" and "fluctuating" SAV beds were either all very close to or well above the minimum light requirement, or the limited set of deviations could be readily explained, confirming the proposed values through the third line of evidence.

From these three lines of evidence, minimum light requirements of 15 percent surface light for mesohaline/polyhaline habitats and 9 percent surface light for tidal fresh/oligohaline habitats were established (Table VII-1). The attainment of the minimum light requirement is tested using the PLL parameter.

Primary and Secondary Habitat Requirements

The minimum light requirement is considered the "primary habitat requirement" (Table VII-1). All the other requirements, including the water-column light requirement, are called "secondary habitat requirements." This nomenclature was chosen because testing the attainment of the minimum light requirement is the primary means for assessing whether an area of shallow water has water quality adequate to support SAV growth, whenever the data needed to calculate PLL are available: light attenuation coefficient (K_d) or Secchi depth, dissolved inorganic nitrogen, dissolved inorganic phosphorus and total suspended solids measurements. SAV habitat quality should be evaluated using the water-column light requirement as a substitute for the minimum light requirement only if the data needed to calculate PLW are available (light attenuation coefficent or Secchi depth) and the parameters needed to calculate PLL, dissolved inorganic nutrients and total suspended solids, are unavailable.

Once the attainment of the minimum light requirement has been tested, the attainment of the secondary habitat requirements should be tested only if the minimum light requirement is not met. Testing attainment of the secondary requirements can suggest possible reasons for non-attainment of the minimum light requirement. The secondary requirements should only be used as diagnostic tools for research or management purposes. See Chapter V for a description of a diagnostic tool based on the total suspended solids and chlorophyll *a* secondary habitat requirements.

If the minimum light requirement is met, but SAV is absent from or sparse in the nearby area, a review of the many factors that can prevent SAV growth should be undertaken (see Chapter VI).

Calculating Percent Light Parameters

Building on their initial descriptions in Chapter V, those applying the minimum light requirements need to understand the following terms.

Z: SAV restoration depth. This is measured from just below the water surface to the sediment-water interface, which is where a submerged plant must start growing. Z is used in formulae for PLW and PLL to specify the path length for light passing through water. This depth is referenced to MLLW or MTL (see below).

PLW: percent light through water. The percent of the light level measured just below the surface of the water that reaches the restoration depth Z, after passing through the overlying water column but not through any epiphytes or associated material on an SAV leaf surface. When Z = 1 meter below MLLW with no tidal range adjustment, PLW is equivalent to K_d (light attenuation coefficient) in the 1992 SAV habitat requirements (Batiuk *et al.* 1992). In this document, both of those conditions are relaxed for PLW as well as PLL: here Z is varied from 0 to 1 meters, and is referenced to mean tidal level with a tidal range adjustment.

PLL: percent light at the leaf. This refers to the percent of light measured just below the surface of the water that reaches the surface of an SAV leaf growing at restoration depth Z (at the sediment-water interface), after passing through the water column and any epiphytes and associated material on an SAV leaf.

MLLW: mean lower low water. This is the mean elevation over time of the lower of the two daily low tides, where there are mixed tides, as in most of Chesapeake Bay. Mixed tides occur when the two high and two low tides each day occur at different elevations. MLLW is used as the reference for the bathymetry on nautical charts to minimize the risk of boats running aground, but it does not estimate the average depth of water (and thus the average path length for light attenuation) above a submerged plant through the day.

MTL: mean tidal level. The midpoint between high and low tides; where there are mixed tides, the midpoint between MHHW (mean higher high water) and MLLW. MTL estimates the average depth of water above a submerged plant (see Chapter VI for details).

PLL calculations require measured values of light attenuation coefficient, total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus (Figure VII-2). The value for K_d can be based on a direct measure of light attenuation calculated by lowering a light meter down through the water column or converted from Secchi depth data using the conversion factor K_d = 1.45/Secchi depth (see Chapter III). However, in some cases there will not be enough monitoring data to calculate PLL, but there will be K_d or Secchi depth data that can be used to calculate PLW. PLW, K_d and PLL are related as follows.

Light measurements (of photosynthetically active radiation, PAR, using a flat cosine sensor) that are needed for PLL and PLW calculations include:

I_o = light level just below surface of the water (usually at 0.1-meter depth); and

I_z = light level at depth Z (often measured at 1.1-meter depth for SAV monitoring; in this example,

z = 1.1-0.1=1.0).

Note that when calculating K_d or PLW from pairs of light measurements, Z represents the difference between the depth of the subsurface light measurement (I_o) and the depth of the deeper light measurement (I_z). Otherwise it represents the restoration depth chosen.

Another light value needed to calculate PLL, I_{ze} (which is not measured directly, but is calculated from K_d, Z, total suspended solids, dissolved inorganic phosphorus and dissolved inorganic nitrogen) is light level at the leaf surface (after passing through the water column as well as any epiphytes and associated material).

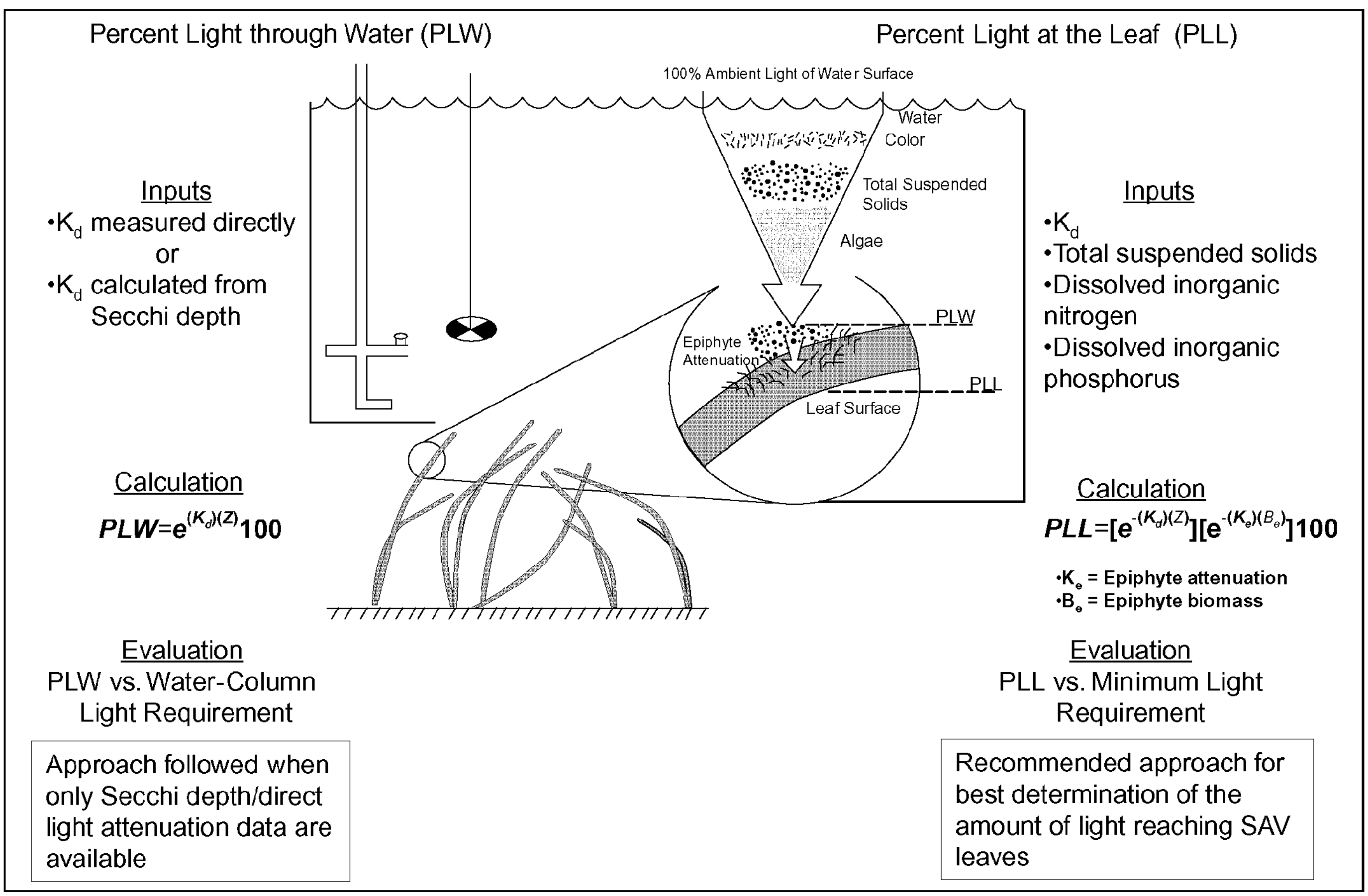

FIGURE VII-2. Calculation of PLW and PLL and Comparisons with their Respective Light Requirements. Illustration of the inputs, calculation, and evaluation of the two percent light parameters: percent light through water and percent light at the leaf.

PLW and PLL can then be expressed as:

$$PLW = I_z/I_o \times 100 \qquad \text{(VII-1)}$$

$$PLL = I_{ze}/I_o \times 100 \qquad \text{(VII-2)}$$

or

$$PLL = [e^{-(K_d)(Z)}]\,[e^{-(K_e)(B_e)}] \times 100 \qquad \text{(VII-3)}$$

from Chapter V, Table V-1.

See Appendix C for the SAS code used to calculate PLL from K_d, total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus. K_d can be converted to PLW, and PLW to K_d as follows:

$$I_z/I_o\ (PLW/100) = e^{-K_d{}^*Z} \qquad \text{(VII-4)}$$

where Z is in meters and the units for K_d are m^1 (Batiuk *et al.* 1992, page 17; Equation VII-2). This would be written in SAS or other programming language to calculate PLW from K_d as:

$$PLW = \exp(-K_d{}^*Z) * 100 \qquad \text{(VII-5).}$$

Taking the natural log of both sides of this equation, K_d can also be calculated from PLW:

$$\ln(PLW) = -K_d{}^*Z + \ln(100), \text{ or}$$

$$K_d = -\ln(PLW/100)/Z \qquad \text{(VII-6).}$$

Because the calculation of PLL includes total suspended solids and dissolved inorganic nutrient data, it cannot be converted to an equivalent K_d value.

Adjusting Percent Light Parameters for Tidal Range and Different Restoration Depths

All of the percent light formulae used in this chapter were adjusted to account for the tidal range. The 1992 K_d requirements (2 or 1.5 m^{-1} depending on salinity, Batiuk *et al.* 1992) used Z = 1 with no adjustment because Batiuk *et al.* (1992) assumed a new plant was growing at the sediment surface with 1 meter of water above it. They assumed that there was (on average) 1 meter of water above the sediment surface at the 1-meter mean lower low water (MLLW) contour, which was called "MLW" in that document. This assumption was incorrect. At the 1-meter MLLW contour there will be 1 meter of water above the plant only once a day, when the lower low tide occurs (assuming mixed tides). Thus, on average, there will be more than 1 meter of water above this point, and the light reaching the sediment surface will be less than what was expected when the 1992 requirements were set.

This greater depth of water above the plant would be offset somewhat as the plant grew and the upper parts were closer to the surface, but the intent of the Chesapeake Bay SAV habitat requirements has always been to predict conditions needed to establish new plants, which must start growing at the sediment surface. The habitat requirements were also intended to predict the conditions needed to restore SAV to a particular shallow water area of the tidal Chesapeake, as defined by the Tier II and Tier III restoration targets (see Chapter VIII). These are the areas of potential SAV habitat to the 1- and 2-meter depth contours, respectively (Batiuk *et al.* 1992). Because those contours were mapped relative to MLLW, the restoration depth (Z) in the percent light formulae must be adjusted with the tidal range to reflect the light conditions at the sediment surface at those depths more accurately. This essentially changes the tidal elevation reference to the mean tidal level (MTL) instead of MLLW. However, NOAA does not provide contours referenced to MTL, since they would be useless for navigation. If the user of these requirements is not interested in predicting water quality conditions needed to restore SAV to a particular restoration depth, they could ignore the tidal range adjustment. For this reason, any users of these percent-light parameters should state in their methods section what Z value(s) were used, and whether any adjustment to Z was made for tidal range.

Before Z can be adjusted for tidal range, value(s) for Z must be chosen. In Batiuk *et al.* (1992), Z = 1 meter was used for the 1-meter restoration requirements and all the K_d calculations, and Z = 2 meters was used only for the 2-meter restoration requirement ($K_d < 0.8\ m^{-1}$), (Table 1, page iii, and Table IV-1, page 27). SAV growth to waters 1-meter deep was thought possible under current light conditions, while growth to the 2-meter depth was judged likely only under greatly improved light conditions, thought to have existed in the 1950s and before, based on the documented deeper growth of SAV in Chesapeake Bay in these time frames.

In this chapter, Z was set to 2, 1, 0.5, 0.25 and 0 meters MLLW, before adjusting it for the tidal range. Some analyses used only some of these depths. The Z value was varied to as low as 0 meters (representing the intertidal zone) because in some segments, particularly the upper tidal Patuxent River, SAV currently grows intertidally. Intertidal growth enables SAV to grow in areas where light conditions are currently too poor to allow SAV growth in deeper water (see below). In other estuaries, Z could be set to any other value where there are different light or tidal conditions or different restoration targets.

Accounting for the tidal range was done by adding half of the tidal range to the value used for Z above (see Appendix D for details on tidal range estimation). It is recognized that this is not the most accurate method to estimate the average light over a tidal cycle, but was selected for simplicity, and any introduced errors are small. Where there are mixed tides as in most of Chesapeake Bay, the tidal range needed is the "diurnal" or "greater tropic" range, defined as (MHHW-MLLW). To show that Z has been varied and has had half the tidal range added to it, the variable names used for calculated values of PLW and PLL are:

PLW(2+) and PLL(2+): Z is set to 2 meters and half the tidal range is added to it;

PLW(1+) and PLL(1+): Z is set to 1 meter and half the tidal range is added to it;

PLW(0.5+) and PLL(0.5+): Z is set to 0.5 meters and half the tidal range is added to it;

PLW(0.25+) and PLL(0.25+): Z is set to 0.25 meters and half the tidal range is added to it; and

PLW(0+) and PLL(0+): Z is set to 0 meters and half the tidal range is added to it.

Although K_d values could also be adjusted using the method described here for PLW and PLL, this was not done to maintain a clear distinction between the 1992 light requirements described here (using K_d assuming Z = 1 meter and no tidal adjustment) and the minimum and water-column light requirements described here (using PLL or PLW respectively, to test their attainment, with a range of Z values and a tidal range adjustment).

All PLL or PLW values are compared to the same respective light requirements (listed in Table VII-1) regardless of which depth Z is used and whether or not they have been adjusted to account for tidal range. That is because the light requirements represent how much light is needed by the plants, regardless of where they are growing. The adjustments to Z to account for tidal range are done to better predict how deep SAV are likely to be able to grow under current light conditions averaged over tidal depth.

Changing the Z values compared to what was used in Batiuk *et al.* (1992) raises the question of what Z value with tidal range adjustment is most comparable to the Z = 1 meter with no tidal range adjustment established in the original SAV technical synthesis in 1992. Since half the tidal range is close to or above 0.5 meters in many segments (see Appendix D, Table D-4), setting Z to 0.5 meters is roughly equivalent to analyses using Z = 1 with no adjustment. This assumption was verified by the analysis of medians over SAV growth categories (see tables VII-2 and VII-4). Thus, PLW(0.5+) will give medians and attainment results most similar to the equivalent K_d values using the 1992 requirements, while PLW(1+) will give a more accurate estimate of the light reaching the 1-meter MLLW depth contour, or a leaf of SAV at that depth contour.

Recommendations for Applying Percent Light Variables and Other Habitat Requirements

Calculate the percent-light variables (PLL or PLW) for a chosen restoration depth Z. If Z is referenced to a depth contour and thus to a depth below MLLW, add half the diurnal tidal range to Z. If Z is referenced to mean tidal level (MTL), do not add half the tidal range to Z. (This assumes that K_d has already been calculated, or Secchi depth has been used to estimate K_d; see above for how to do this.)

Choose the restoration depth(s) Z based on local conditions. In Chesapeake Bay we have targets to restore SAV to shallow water areas to 1- and 2-meter depths below MLLW (see Chapter VIII), but in some cases we have set Z to shallower depths (see above).

Use (or collect) K_d data rather than Secchi depth if both are available. K_d is based on the light wavelengths used in photosynthesis and Secchi depth uses visual light. Also, K_d can be measured more accurately in clear, shallow waters where the Secchi disk is still visible on the bottom.

Calculate PLL whenever the data needed for it are available (K_d or Secchi depth, total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus). Since the minimum light requirement (which is tested with PLL data) is the primary or most useful single habitat requirement, PLL data are needed to test it. Calculate PLW when K_d or Secchi data are available, but one or more of the other parameters needed for PLL calculations are not available.

Use water quality measurements from the "surface" layer (usually 0.1- to 0.5-meters deep, sometimes 1-meter deep). These measurements, along with K_d or Secchi depth data, should come from water quality monitoring station(s) as close as possible to the potential habitat or actual SAV bed of interest.

Collect water quality data for calculating parameters used to test minimum light requirement attainment during the SAV growing season only. In Chesapeake Bay this is April-October (7 months) for tidal fresh, oligohaline and mesohaline areas. In polyhaline areas, where eelgrass (*Zostera marina*) is dominant, the growing season is March-May and September-November (6 months), due to summer dieback of eelgrass. Sampling frequency should be at least monthly. If there are missing data, no tests of attainment should be done unless there are data from at least four different months during the SAV growing season.

Where eelgrass is present in mesohaline areas, or extensive widgeongrass (*R. maritima*) is present in polyhaline areas, it may be informative to calculate medians using both growing seasons. In other estuaries, the local growing season should be determined for each of the dominant species from SAV biomass and water temperature measurements over at least one year.

Test the attainment of PLL values by comparing their growing season medians to the minimum light requirement for the applicable salinity regime (9 percent or 15 percent; see Table VII-1). Attainment of PLW values is tested by comparing them to the water-column light requirement for the applicable salinity regime (13 percent or 22 percent; see Table VII-1).

Test the attainment of the minimum light requirement or the water-column light requirement in one of two ways: by calculating PLL or PLW medians and determining if they are greater than or less than the minimum light requirement or water-column light requirement, respectively, or by a nonparametric statistical test. If software to perform the statistical test is available, it should be used, rather than the median comparison, since it uses more of the information in the data. The two methods are:

1. To compare median PLL or PLW values over the SAV growing season to the minimum light requirement or the water-column light requirement. If the medians are greater than the minimum light requirement or water-column light requirement, the requirement is "Met"; if the median is less than or equal to the minimum light requirement or water-column light requirement, the requirement is "Not Met."
2. To perform a statistical test by calculating the difference between the individual measurements of the percent light parameter used, PLL or PLW, and the appropriate minimum light requirement or water-column light requirement, respectively, and running a nonparametric sign test on the difference variable. This tests the null hypothesis that the difference is zero, or that there was no difference between the measured data, PLL or PLW, and the minimum light requirement or water-column light requirement, respectively. See Appendix D for details; the three outcomes are called "Met," "Borderline" or "Not Met."

EVALUATING MINIMUM LIGHT REQUIREMENTS USING CHESAPEAKE BAY WATER QUALITY MONITORING DATA AND SAV SURVEY DATA

The next four sections of this chapter use Chesapeake Bay water quality monitoring data and SAV distribution data to evaluate the minimum light requirements that were set above and to see how useful the percent light at the leaf parameter is in testing their attainment. These evaluations are not attempting to test the model used to develop the percent light at the leaf calculations, since most of the monitoring data (both for water quality and SAV area) available were collected over too broad a spatial and temporal scale to be used for that purpose. The goal of the next four sections was to see how well the results of analyses of baywide monitoring data fit with expectations in four different areas:

1. Was there better median water quality where there was more SAV growth, and worse median water quality where there was less or no SAV growth?
2. Are there segments where the minimum light requirements consistently failed, that had SAV

growing in them? If so, can we determine reasons for this apparent paradox?

3. Were the percent light parameters and other SAV habitat requirements significantly correlated with measures of SAV area by Chesapeake Bay Program segment and year, regardless of the depth at which it was growing?

4. Were the percent light parameters and other SAV habitat requirements significantly correlated with measures of SAV area by Chesapeake Bay Program segment and year over four depth categories?

Where there are discrepancies, these may be productive areas for future research, which usually would involve more detailed monitoring of both water quality and SAV abundance. There are many other similar questions that could be asked. The water quality and SAV area data are available through the Chesapeake Bay Program and Virginia Institute of Marine Science web sites, (www.chesapeakebay.net and www.vims.edu/bio/sav, respectively) for researchers and managers who want to explore other questions. The two key fields linking the two data sets are Chesapeake Bay Program segment and year. Data for both water quality and SAV area are available for each year from 1985 onward, except for 1988, when the SAV survey was not conducted due to budget constraints. There are 78 Chesapeake Bay Program segments, but only 69 of them have water quality data available. These segments vary in overall size and in the extent of shallow water habitat. For that reason, in many of the analyses described below, the SAV area measured in a segment was divided by the extent of shallow water habitat in that segment, measured as the "Tier II" area (see Chapter VIII for a definition). Most of the water quality data were measured at midchannel stations, often in fairly deep water, which may limit their usefulness in these types of analyses (see Chapter IX).

COMPARING WATER QUALITY MEDIANS OVER CATEGORIES OF SAV GROWTH

For this section, medians of nearshore water quality data (from the Choptank and York rivers) and Chesapeake Bay Monitoring Program midchannel data were assessed for empirical relationships with SAV growth categories. It was expected that medians would be better where there was more SAV growth and worse where there was less growth. "Better" here means lower levels for K_d, total suspended solids, chlorophyll *a*, dissolved inorganic phosphorus, dissolved inorganic nitrogen and higher levels (more light) for PLW and PLL. The point at which the habitat requirements fell among the medians over the different growth categories was used as an empirical check on the values chosen for the habitat requirements. The comparisons using Chesapeake Bay Program midchannel water quality data are a less rigorous test of the habitat requirements than those using nearshore data, since the Bay water quality monitoring stations may be several kilometers or more from shallow water SAV habitat, and Bay water quality monitoring stations were not placed along gradients of SAV growth. The 1992 SAV habitat requirements were based on the nearshore data analyzed here, but have not been checked with Bay water quality monitoring data using this method.

Methods

Three growth categories were used for analyses using nearshore water quality data and five growth categories for analyses using midchannel water quality data; see Appendix D for definitions of the categories. The tidal fresh and polyhaline salinity regimes had segments falling in only four of the five growth categories.

The ranges of annual seasonal median nearshore water quality over SAV growth categories were used in Batiuk *et al.* (1992) to help determine the habitat requirements. The authors of that document examined the maximum medians at monitoring stations near healthy or fluctuating SAV beds and used those to help set the habitat requirement (it was not always set at the maximum). The assumption was that if some SAV were growing near the station with the maximum median, then SAV should be able to grow at similar sites where that median water quality occurs. This approach was used here as an empirical check or verification of the 1992 habitat requirements, rather than as a way to derive the requirements.

For the nearshore data, maxima of the annual growing season medians by station were used, as in Batiuk *et al.* (1992) (or minima for PLL/PLW), while for the Chesapeake Bay Program midchannel monitoring data, medians of the annual growing season medians by segment were used. The midchannel stations are not as close to SAV beds as the nearshore stations, and the SAV growth categories for CBP midchannel data are based on aerial survey data, not on transplant success nearby. The more general nature of these data argued for using medians instead of maxima. Maxima could be used for the nearshore data because the stations were near SAV beds. In the midchannel data, if maxima are used, they are generally worse than the habitat requirements, even in segments with SAV. This is probably because midchannel stations tend to be farther from SAV than the nearshore stations.

Kruskal-Wallis nonparametric ANOVA was used to compare differences among the median water quality values over different categories of SAV growth, using the NPAR1WAY procedure in SAS. This analysis tests the null hypothesis that all the SAV growth categories had the same median water quality. Statistically significant differences ('ANOVA P' < 0.05 in the following tables, shown in bold) show that water quality differed among segments in the different SAV growth categories, which is the expected outcome for water quality parameters that affect SAV growth.

Results and Discussion

Minima of annual growing season medians of nearshore monitoring data from the Choptank and York rivers (mesohaline and polyhaline, respectively) for the percent light habitat requirement parameters are shown in Table VII-2. Maxima of annual growing season medians for the secondary habitat requirement parameters other than PLW are shown in Table VII-3. Both tables group the data using three categories of SAV growth based on the persistence of SAV transplants near the monitoring stations. Data from 1986-1989 were used in both tables; these are the same data that were analyzed by Batiuk *et al.* (1992) to set the original SAV habitat requirements for Chesapeake Bay.

Medians of annual growing season median values from Chesapeake Bay Program midchannel water quality monitoring stations by salinity regime for the percent light habitat requirement parameters are shown in Table VII-4. Medians of annual growing season median values for the secondary habitat requirement parameters other than PLW from the same stations

TABLE VII-2. Minima of annual SAV growing season medians of percent-light parameters from Choptank and York River nearshore monitoring stations by salinity regime and nearby SAV growth category, compared to the minimum light requirement and water column light requirement values shown, and Kruskal-Wallis ANOVA P for differences among categories, using 1986-1989 data and adding half the tidal range to the restoration depth Z value listed for the percent light through water (PLW) and percent light at the leaf (PLL).

Salinity Regime	SAV Growth	PLW (2+)	PLW (1+)	PLW (0.5+)	PLW (0.25+)	PLL (2+)	PLL (1+)	PLL (0.5+)	PLL (0.25+)	N
			WCLR = 22%				MLR = 15%			
Mesohaline	Persistent	3.2%	14.5%	31.1%	45.4%	3.0%	13.5%	28.8%	42.1%	11
(Choptank)	Fluctuating	1.5%	9.3%	22.9%	36.1%	1.4%	7.9%	16.1%	25.9%	19
	None	0.0%	0.4%	3.3%	9.3%	0.0%	0.4%	2.0%	4.6%	18
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	
			WCLR = 22%				MLR = 15%			
Polyhaline	Persistent	5.2%	17.8%	32.3%	44.7%	4.0%	12.8%	22.2%	30.7%	11
(York)	Fluctuating	3.5%	14.0%	28.2%	40.0%	2.4%	9.1%	16.1%	20.7%	7
	None	0.5%	4.1%	12.2%	21.2%	0.4%	3.1%	8.2%	13.4%	7
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	

Note: Double lines separate values above and below the habitat requirement. For all of these parameters, less is worse (less light). P values from Kruskal-Wallis nonparametric one-way ANOVA showing significant differences among growth categories (at P < 0.05) are in **bold**. WCLR = water-column light requirement. MLR = minimum light requirement. N is the number of station x year combinations in that category.

TABLE VII-3. Maximum of annual SAV growing season medians compared to secondary habitat requirements, other than PLW, from Choptank and York River nearshore monitoring stations by salinity regime and SAV growth category, and Kruskal-Wallis ANOVA results, using 1986-1989 water quality data for total suspended solids (TSS), chlorophyll *a* (CHLA), dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN).

Salinity Regime	SAV Growth	TSS	CHLA	DIP	DIN	N
Mesohaline	Persistent	14.0	11.5	0.0055	0.167	11
(Choptank)	Fluctuating	22.0	13.2	0.0136	0.223	19
	None	36.5	38.5	0.0498	1.55	26
ANOVA P		**0.0001**	**0.0038**	**0.0001**	**0.01**	
Polyhaline	Persistent	13.8	11.0	0.0260	0.128	11
(York)	Fluctuating	21.1	13.4	0.0369	0.173	7
	None	25.6	20.6	0.0499	0.182	7
ANOVA P		**0.0011**	0.42	**0.0004**	0.101	

Note: Double lines separate values above and below the habitat requirement. For all of these parameters, more is worse. P values from Kruskal-Wallis nonparametric one-way ANOVA showing significant differences among growth categories (at P < 0.05) are in bold. N is the number of station x year combinations in that category.

are shown in Table VII-5. Both tables group the data using five categories of SAV growth based on the median, minimum and maximum SAV area mapped in the same CBP segment from 1978-1997 (see Appendix D for methods). Water quality data from 1985-1998 were used in both tables.

ANOVA significance levels (P values) show that almost all of the medians of these parameters differed significantly among the categories of SAV growth, which was expected. The exceptions were chlorophyll *a* and dissolved inorganic nitrogen in the York River (Table VII-3) and total suspended solids and chlorophyll *a* in polyhaline areas (Table VII-5). Significant differences among growth categories were not expected in two of these four cases because all the medians for total suspended solids and chlorophyll *a* in polyhaline areas in Table VII-5 were better than the total suspended solids and chlorophyll *a* habitat requirements set in Batiuk *et al.* (1992). The polyhaline regime also has fewer segments and thus had among the smallest sample sizes in Table VII-5, making it more likely that ANOVA results will not be significant.

The point at which the established SAV habitat requirements fell among the medians over growth categories is shown with a double line under or over those cells in tables VII-2 through VII-5 and as horizontal lines for the minimum light requirement in Figure VII-3. In most salinity regimes, segments with median water quality better than the habitat requirements had some SAV, while those with median water quality worse than the habitat requirements had less or no SAV. This was the expected pattern, which can also be seen in Figure VII-3 for PLL wherever at least one bar crosses the dashed line representing the minimum light requirements. Note that the y-axis scales are different in low- and high-salinity regimes in Figure VII-3. The median of PLL(0.5+) was greater (better) than the minimum light requirement for the Always Abundant growth category in all salinity regimes except oligohaline, but the PLL(1+) median was greater (better) than the minimum light requirement for the Always Abundant category in mesohaline and polyhaline regimes only. The PLL(1+) median was also near or above the minimum light requirement for the Sometimes None and Always Some categories in mesohaline and polyhaline regimes.

TABLE VII-4. Medians of annual SAV growing season medians of percent light parameters from Chesapeake Bay Program midchannel water quality monitoring stations, by salinity regime and SAV growth category compared to the minimum light requirement and water column light requirement values shown, and Kruskal-Wallis ANOVA P for differences among categories, using 1985-1998 data and adding half of the tidal range to Z for the percent light through water (PLW) and percent light at the leaf (PLL) parameters.

Salinity Regime	SAV Growth	PLW (2+)	PLW (1+)	PLW (0.5+)	PLW (0.25+)	PLL (2+)	PLL (1+)	PLL (0.5+)	PLL (0.25+)	N
			WCLR = 13%				MLR = 9%			
Tidal fresh	AA	1.4%	8.5%	20.9%	33.0%	1.3%	7.8%	18.1%	27.3%	14
	SN	0.1%	1.7%	7.5%	15.4%	0.1%	1.4%	5.6%	11.1%	53
	UN	0.0%	0.3%	2.2%	5.7%	0.0%	0.3%	1.3%	3.0%	14
	AN	0.1%	2.5%	9.8%	20.1%	0.1%	1.9%	6.6%	12.9%	81
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	
			WCLR = 13%				MLR = 9%			
Oligohaline	AA	0.5%	5.4%	18.2%	33.2%	0.4%	3.2%	8.5%	14.1%	13
	AS	0.3%	3.3%	11.1%	21.3%	0.3%	2.3%	7.1%	11.6%	42
	SN	0.0%	0.9%	5.4%	13.4%	0.0%	0.8%	4.3%	10.1%	56
	UN	0.0%	0.7%	4.5%	11.1%	0.0%	0.6%	3.8%	7.5%	25
	AN	0.0%	0.5%	3.3%	9.3%	0.0%	0.3%	2.2%	5.5%	92
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	
			WCLR = 22%				MLR = 15%			
Mesohaline	AA	10.9%	29.4%	47.8%	60.9%	10.1%	25.8%	41.3%	53.0%	28
	AS	6.4%	21.6%	39.5%	53.5%	5.8%	18.4%	32.7%	44.4%	125
	SN	3.9%	15.9%	32.9%	47.7%	3.5%	14.1%	27.9%	38.8%	95
	UN	1.7%	10.3%	24.9%	39.9%	1.5%	7.8%	19.4%	30.7%	98
	AN	0.1%	1.9%	8.0%	16.1%	0.1%	1.5%	5.3%	10.3%	47
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	
			WCLR = 22%				MLR = 15%			
Polyhaline	AA	11.1%	28.5%	44.8%	57.4%	9.8%	24.8%	40.1%	50.9%	42
	AS	6.7%	20.5%	36.1%	47.8%	5.0%	13.2%	22.4%	29.6%	14
	SN	5.7%	18.4%	33.3%	44.8%	4.4%	13.1%	21.9%	28.5%	14
	AN	2.9%	12.2%	25.1%	36.1%	2.1%	8.1%	15.0%	20.5%	14
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	

Note: Double lines under a cell separate values above and below the water-column light requirement (WCLR) or minimum light requirement (MLR) shown. Numbers in parentheses are the restoration depth (Z) to which half the tidal range was added before calculations. For all parameters, less is worse (less light). P values from Kruskal-Wallis nonparametric one-way ANOVA showing significant differences among growth categories (at P < 0.05) are in **bold**. N is the number of segment x year combinations in that category. AA = always abundant; AS = always some; SN = sometimes none; UN = usually none; and AN = always none.

TABLE VII-5. Medians of annual SAV growing season medians of parameters with secondary SAV habitat requirements other than PLW, from Chesapeake Bay Program midchannel water quality monitoring stations by salinity regime and SAV growth category, and Kruskal-Wallis ANOVA P for differences among categories, using 1985-1998 water quality data for total suspended solids (TSS), chlorophyll *a* (CHLA), dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN).

Salinity Regime	SAV Growth	TSS	CHLA	DIP	DIN	N
Tidal fresh	AA	9.975	8.825	0.006	0.9409	14
	SN	20	23.8	0.015	0.6643	53
	UN	24.025	19.375	0.0328	1.1708	14
	AN	17	7.6942	0.02	0.37	81
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	
Oligohaline	AA	17	4.65	0.0465	0.859	13
	AS	18.5	8.175	0.0139	0.636	42
	SN	25	28.65	0.005	0.115	56
	UN	27.3	17.37	0.0234	0.146	28
	AN	32.75	13.03	0.02	0.2255	98
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	
Mesohaline	AA	7.95	8.1	0.004	0.079	28
	AS	10.5	9.15	0.007	0.105	125
	SN	11	10	0.005	0.082	95
	UN	15	15.15	0.01	0.091	98
	AN	27	11.89	0.015	0.1765	47
ANOVA P		**0.0001**	**0.0001**	**0.0001**	**0.0001**	
Polyhaline	AA	10	6.3479	0.003	0.045	42
	AS	9.75	5.8613	0.01	0.1175	14
	SN	11.05	7.1324	0.0147	0.1403	14
	AN	11.5	5.95	0.0245	0.21	12
ANOVA P		0.50	0.59	**0.0001**	**0.0001**	

Note: Double lines under a cell separate values above and below the respective habitat requirement; see Table VII-1 for values. For all parameters, more is worse. P values showing significant differences among growth categories (at $P < 0.05$) are in **bold**. N is the number of segment x year combinations in that category. AA = always abundant; AS = always some; SN = sometimes none; UN = usually none; and AN = always none.

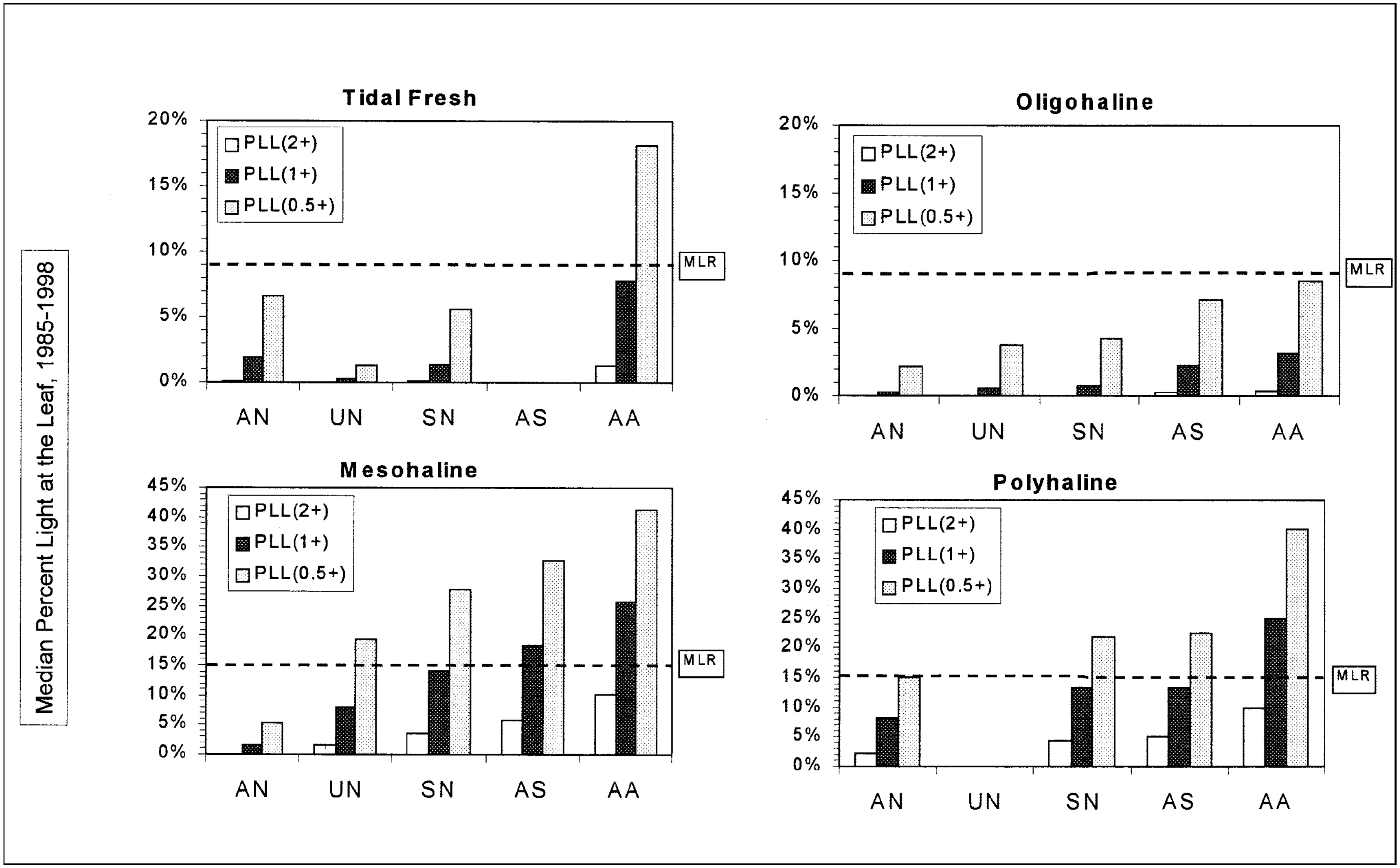

FIGURE VII-3. Comparison of PLL Values for Different Restoration Depths Across Salinity Regimes by SAV Abudance Category. SAV growing season median percent light at the leaf (PLL) was calculated using 1985-1998 Chesapeake Bay Water Quality Monitoring Program data by SAV relative abundance category. AN = Always None, UN = Usually None, SN = Sometimes None, AS = Always Some, AA = Always Abundant. The applicable minimum light requirement (MLR) for each salinity regime is illustrated as a dashed line. The number with plus symbol within parentheses after PLL indicates the restoration depth (in meters) adjusted for tidal range.

There were a few deviations, however, from the expected pattern in some segments.

- PLW(2+) and PLL(2+) medians were worse than their applicable water-column and minimum light requirements, respectively, in all categories (Table VII-4, Figure VII-3).
- The oligohaline midchannel medians for several parameters—total suspended solids, PLW(1+), PLL(1+) and PLL(0.5+)—in tables VII-4 and VII-5 were worse than the habitat requirements in all growth categories, even in the one segment (POTOH) in the highest SAV growth category (Always Abundant). However, the median for PLW(0.5+) was better than the water-column light target in the Always Abundant category, and thus fit the expected pattern.
- The tidal fresh midchannel medians for PLW(1+) and PLL(1+) were also worse than the light requirements and targets in all growth categories, although the medians for PLW(0.5+) and PLL(0.5+) were better than the respective water-column and minimum light requirements in the Always Abundant category, and thus fit the expected pattern (Table VII-4).
- In the polyhaline nearshore data the maximum median for dissolved inorganic phosphorus in the 'Persistent' category, 0.026 mg/l, was just above the dissolved inorganic phosphorus habitat equirement, 0.02 mg/l (Table VII-3).
- In polyhaline segments using the Chesapeake Bay Program water quality monitoring midchannel data, the total suspended solids and chlorophyll *a* medians were all better (lower) than the habitat requirements (Table VII-5).
- In the nearshore data, the minima of mesohaline and polyhaline medians for PLW(1+) and PLL(1+) were all worse than the light requirements (Table VII-2).

Of the six deviations described above, only the last one appears to require further scrutiny, for the following reasons:

- In the first deviation, we do not expect restoration for 2 meters to be possible under current conditions.
- The next two deviations are in tidal fresh and oligohaline segments, where the match between habitat requirement attainment and the presence of SAV is not as close as in higher salinity segments, due partly to the very shallow depth distribution of SAV in some low salinity segments.
- The fourth deviation is minor, affecting only one parameter–dissolved inorganic phosphorus.
- The fifth deviation was found in midchannel monitoring data, which is often collected relatively far from the SAV beds in polyhaline segments, given the relatively large size of these higher salinity segments.

This leaves as a problem to be explained, the sixth deviation, the fact that all the PLW(1+) and PLL(1+) medians from nearshore data from the Choptank and York rivers were worse than the respective light requirements, including those from stations near "Persistent" SAV beds (Table VII-2). Likely reasons for these deviations are as follows.

As noted above, half the tidal range is close to or above 0.5 meters in many segments (0.3 meters and 0.4 meters, respectively, in these Choptank and York segments), so setting Z to 0.5+ in these analyses (rather than 1+) is closer to the analyses in Batiuk *et al.* (1992) that were used to derive the 1992 K_d requirements, in which Z = 1 with no tidal range adjustment. For PLW(0.5+) and PLL(0.5+) in Table VII-2, the minimum and water-column light requirements fell between the medians for "Fluctuating" and "None" categories, exactly as would be expected based on what the requirements mean. Most of the PLW(0.5+) and PLL(0.5+) medians in tidal fresh and oligohaline segments were also consistent with expectations (except PLL(0.5+) in oligohaline segments) (Table VII-4).

In both rivers, the extreme values that set the minima for PLW and PLL either came from a single station and year, and the next larger median was consistent with the requirement or target, or the minima were not that much lower than the requirement. In the Choptank River mesohaline data, many of the extreme values came from a single station and year, Chapel Creek in 1986. Without these anomalous data, in the "Persistent" category the minimum PLW(1+) median was 22.1 percent instead of 14.5 percent, and the PLL(1+) median was 21.3 percent instead of 13.5 percent, both of which are better than the water-column light requirement and minimum light requirement for that salinity regime (22 percent and 15 percent, respectively).

In the York River polyhaline data, the minimum for PLW(1+) for "Persistent," 17.8 percent, was from a single station and year (Guinea Marsh in 1987); the next higher PLW(1+) values, 19.6 percent and 21.3 percent, were closer to the water column light requirement of 22 percent. The minimum for PLL(1+) in that segment, 12.8 percent, was close to the minimum light requirement for that salinity regime (15 percent); the two next higher values in the "Persistent" category were 13.3 percent and 14.1 percent.

Thus, it appears that the minimum and water-column light requirements do not need to be adjusted to account for any of the discrepancies noted above, when comparing them to the medians over growth categories from midchannel and nearshore water quality monitoring data.

Another more general comparison was done to check if segments with better water quality tended to have more SAV. One would generally expect the best water quality where there was the most SAV, and the worst water quality where there is the least SAV, in this sequence: Persistent > Fluctuating > None for nearshore data, or Always Abundant (AA) > Always Some (AS) > Sometimes None (SN) > Usually None (UN) > Always None (AN) for midchannel data.

The maximum, minimum and median levels in tables VII-2 through VII-5 were usually, but not always, directly proportional to the amount of SAV present. This pattern was seen most clearly in the nearshore data (tables VII-2 and VII-3) and in the mesohaline and polyhaline segments in tables VII-4 and VII-5.

IDENTIFYING SEGMENTS WITH PERSISTENT FAILURE OF THE MINIMUM LIGHT REQUIREMENTS AND CHECKING THEM FOR SAV GROWTH

Each Chesapeake Bay Program segment with water quality data was compared to determine whether consistent failure of the minimum light requirement predicted a lack of SAV growth. This was done by looking for any Chesapeake Bay Program segments with persistent failure of the minimum light requirement that contained appreciable amounts of SAV (over 35 hectares). In these segments, possible reasons for the mismatch were examined. The corresponding analysis, checking for segments with the minimum light requirement usually met where there was little or no SAV, would not be useful because SAV can be lacking for a variety of reasons (lack of propagules, high wave action, etc.).

Methods

Chesapeake Bay Program segments with PLL medians failing the minimum light requirements more than half of the years from 1992-1997 were tabulated using the sign test at P = 0.05 and the FREQ procedure in SAS. The restoration depth (Z) was varied over 1, 0.5, 0.25 and 0 meters plus half the tidal range. Segments were identified as persistently failing the minimum light requirements at the lowest (worst) depth if they had failed half or more of the years. The 1997 SAV area was checked for each of the segments with persistent failure at 0.5 meters or less, and the segment was flagged as a problem segment if the SAV area was over 35 hectares (86 acres). The expectation was that SAV would not grow where the minimum light requirement was failed persistently. This SAV hectare cutoff was somewhat arbitrary, but was chosen to leave out some small segments (such as the Northeast and Bohemia rivers) that contain very small amounts of SAV, sometimes a single bed. For each of the problem segments, possible reasons for the presence of SAV were examined.

Results and Discussion

Figure VII-4 shows the Chesapeake Bay Program segments with median PLL values failing the minimum light requirement at different Z values half of the years or more between 1992 and 1997. Those segments failing at Z = 0.5 meters or less are identified by name. Of that group, there were only two problem segments, Patuxent tidal fresh and oligohaline. Both segments failed the minimum light requirement at Z = 0.25 meters plus half the tidal range and had more than 35 hectares of SAV in 1997. It is likely that they contain SAV in spite of the poor light conditions because most of the SAV present in both segments is growing in very shallow water, including some growing in the intertidal zone.

COMPARING DIFFERENT SAV HABITAT REQUIREMENTS AS PREDICTORS OF SAV AREA

Correlations of annual estimated SAV area with annual median water quality were used to test the ability of each of the 1992 SAV habitat requirements and the two

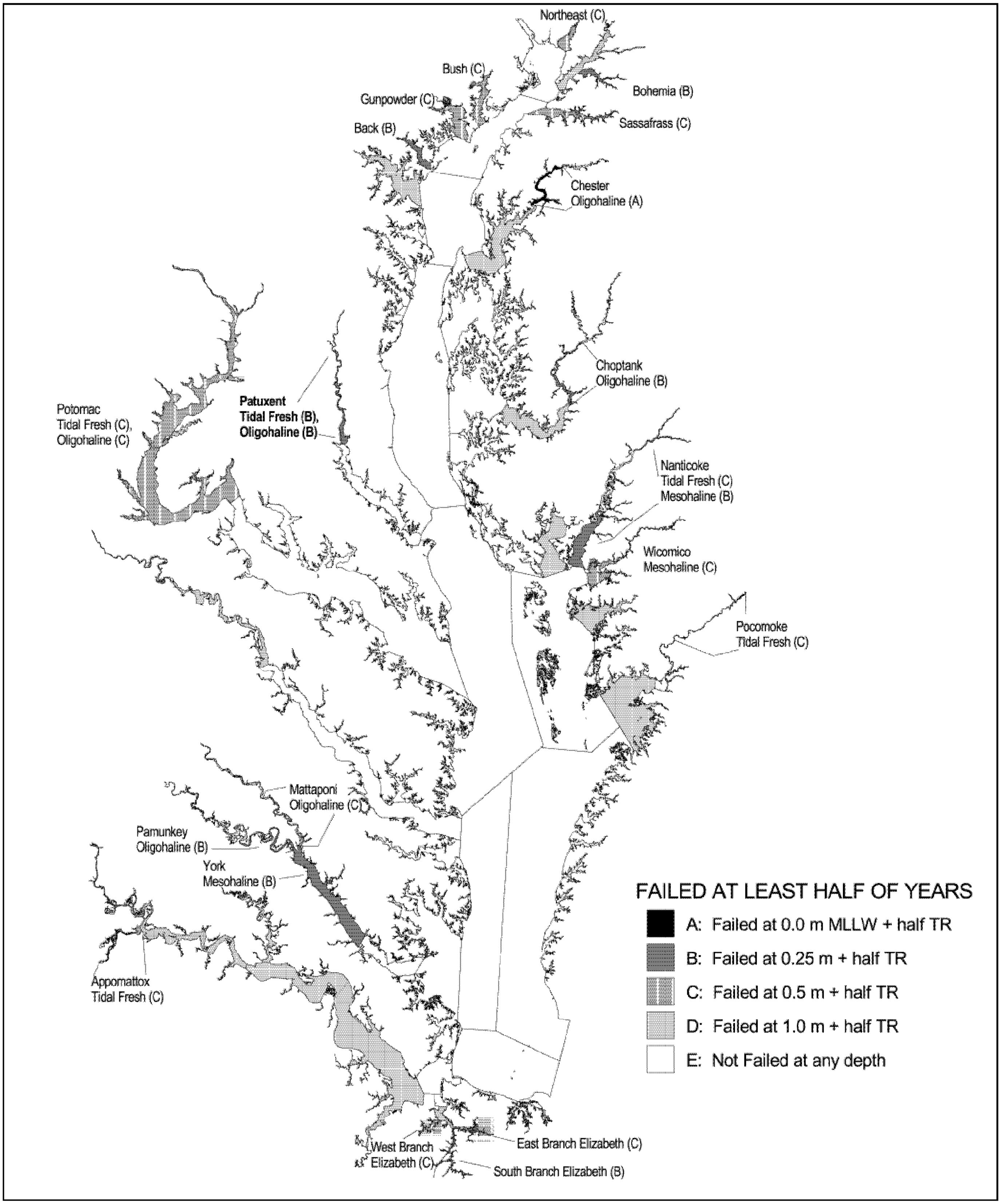

FIGURE VII-4. Segments Failing PLL Requirements Half of the Years of More, 1992-97. Chesapeake Bay Program segments with SAV growing season median PLL values failing the minimum light requirement half the years or more between 1982 and 1997. Only the Chesapeake Bay Program segments in categores A, B, and C are labeled. TR = diurnal tidal range. Segment names in bold indicate both the Patuxent tidal fresh and oligohaline segments had PLL failed at 0.25 meter + half TR (category B) or less, AND appreciable amounts (>35 ha) of SAV.

percent-light parameters to predict SAV area. This ability is a desirable feature of any SAV habitat requirements, since it justifies using the habitat requirements to set nutrient and sediment reduction targets and to target the best areas for SAV restoration. However, any lack of significant correlations in this analysis does not invalidate the model used to derive PLL. Most of the data used were collected in large-scale monitoring programs, and not over the small spatial and temporal scales needed for a research project.

In this analysis it was expected that light parameters (K_d, PLW and PLL) would have stronger and more significant correlations with SAV area than other habitat requirement parameters, since ecological models show that light is the primary factor limiting SAV distribution in Chesapeake Bay (Batiuk *et al.* 1992; chapters III and V).

Methods

Correlations were calculated with the SAS procedure CORR between SAV area in hectares, by year, and median water quality from the Chesapeake Bay Program water quality monitoring stations, by year. Nearshore water quality data were not used because they do not have associated SAV area data. Spearman rank correlation (nonparametric) was used rather than Pearson (parametric) correlation, because SAV area is not normally distributed, even with transformations, due largely to the large number of zeroes. The zeroes make SAV area a difficult variable to use in correlations, even Spearman correlations. Another problem is that in many salinity regimes most or all of the segments and years with high SAV area are in only one or two segments, so the results may reflect conditions in those segments rather than in the all the segments in the salinity regime. In Spearman correlations, if the two data sets are ranked exactly the same way, r_s = +1; if they have opposite ranks, r_s = -1, and 0 means no association. For example, to be ranked the same way, the segment and year with the highest PLL median would have the highest SAV area; the second highest PLL would have the second-highest SAV area; and so on. When there are ties (as with the many zeroes) they all receive the same rank, making it harder to find a significant correlation. When discussing correlations the terms "stronger" and "weaker" are used to mean "larger (or smaller) absolute value of r_s" since for some water quality parameters the expected correlations with SAV area are positive (PLW and PLL, more light means more SAV), and for others they are negative (all other parameters, more pollution means less SAV).

The spatial units used for this analysis were the 69 Chesapeake Bay Program segments that have water quality data, grouped into salinity regimes. The time periods over which water quality medians were calculated were the SAV growing season (April-October except in polyhaline where it is March-May and September-November), or in spring (April-June, except March-May in polyhaline segments). Spring data were tested separately to see if spring water quality was more important than water quality over the whole growing season. After spring, many species are growing at or near the surface, and thus their survival and growth might be less sensitive to water quality conditions in the summer and fall.

Three different measures were used for SAV area measured in the same year as the water quality data: SAV hectares (SAVH), SAVH as a percent of Tier II area (PCT_T2), and SAVH as a percent of Tier III area (PCT_T3). The latter two measures were calculated to correct for the differing amounts of potential SAV habitat in different CBP segments, which differ greatly in size.

Lagged effects were tested two ways, by replacing SAV area from the current year (SAVH) with SAV area from the following year (LAGSAVH) or replacing it with the change in SAV area from this year to the following year (CHGSAVH). The expected correlations were negative for K_d, total suspended solids, chlorophyll *a*, dissolved inorganic phosphorus and dissolved inorganic nitrogen, since for these parameters higher levels should lead to a reduction in SAV area, and positive for PLW and PLL. Both K_d and PLW were included because PLW calculations included the tidal range adjustment for Z, while those for K_d did not.

Results and Discussion

Results are summarized in Table VII-6, and complete results are given in Appendix E, tables E-1, 3, 5 and 7 over the whole growing season and in Appendix E, tables E-2, 4, 6 and 8 over the spring portion of the growing season. These correlations show the following over the whole SAV growing season:

TABLE VII-6. Salinity regimes that had statistically significant ($P < 0.05$) Spearman rank correlation coefficients in expected directions, between water quality parameters from Chesapeake Bay Program midchannel water quality stations and measures of SAV area over Chesapeake Bay Program segments (see Appendix E, tables E-1 through E-8 for correlations, P values and sample sizes).

Water Quality Parameter	SAV Area Parameter				
	PCT_T2	**PCT_T3**	**SAVH**	**LAGSAVH**	**CHGSAVH**
K_d	OH+	OH+	OH+	OH+	
	MH+	**MH+**	**MH+**	**MH+**	
	PH+	PH+	**PH+**	**PH+**	
PLW(1+)	OH+	OH+	OH+	OH+	
	MH+	**MH+**	**MH+**	**MH+**	
	PH+	PH+	**PH+**	**PH+**	
PLL(1+)	OH+	OH+	OH+	OH+	
	MH+	**MH+**	**MH+**	**MH+**	MH
	PH+	**PH+**	**PH+**	**PH+**	
TSS	**TF**	**TF**		**TF**	
	OH+	**OH+**	**OH+**	**OH+**	
	MH+	MH+	MH+	MH+	
CHLA			OH	OH	
	MH+	MH+	MH+	MH+	
				PH#	
DIP		TF+	TF+	TF+	
	OH#	OH#	OH#	OH#	
	MH+	MH+	MH+	MH+	
	PH+	**PH+**	**PH+**	**PH+**	
DIN	MH#	MH+	MH+	MH+	
	PH	**PH**	**PH+**	**PH+**	PH+

KEY: PCT_T2 = SAVH/Tier II area*100, PCT_T3 = SAVH/Tier III area*100, SAVH=SAV hectares for same year as water quality data; LAGSAVH=SAV hectares for following year; CHGSAVH=change in SAV hectares from that year to next. TF = tidal fresh, OH = oligohaline, MH = mesohaline, and PH= polyhaline (see Table VII-1 for salinities).
Light attenuation coefficient = K_d; percent light through water = PLW; percent light at the leaf = PLL; total suspended solids = TSS; chlorophyll *a* = CHLA; dissolved inorganic phosphorus = DIP; and dissolved inorganic nitrogen = DIN.
Regimes in bold had correlations >+/- 0.5 over the whole growing season; some were > 0.5 over the spring also.
+ Also had significant correlation over spring part of growing season (if no symbol, significant over whole year).
# Significant correlation over spring part of growing season only (April-June except March-May in polyhaline).

In oligohaline, mesohaline and polyhaline segments, four of the five SAV area parameters (all but CHGSAVH) showed the expected statistically significant correlations ($P < 0.05$) with the three light parameters: more light meant more SAV (negative correlations for K_d, positive for PLW and PLL). The r_s values were near 0.35 for oligohaline and 0.55 for mesohaline and polyhaline segments.

Most of the other habitat requirement parameters tested had weaker but significant correlations in these three salinity regimes, but the correlations were not significant for dissolved inorganic nitrogen in oligohaline or total suspended solids and chlorophyll *a* in polyhaline segments (except that chlorophyll *a* had a significant correlation with LAGSAVH in the spring). Oligohaline dissolved inorganic nitrogen was not expected to correlate with SAV area because there is no habitat requirement for dissolved inorganic nitrogen in tidal fresh and oligohaline segments.

Tidal fresh segments showed weaker correlations but they were statistically significant for most area parameters for total suspended solids and dissolved inorganic phosphorus.

The expected significant relationships were stronger for PLL than for PLW in polyhaline segments, and almost the same in other segments where they were significant (oligohaline and mesohaline segments). Correlations for K_d differed from those for PLW because K_d was not adjusted for tidal range.

The three different measures of SAV area in the same year as the water quality data (PCT_T2, PCT_T3, and SAVH) usually had similar, significant correlations with water quality variables over the whole growing season, with a few exceptions. In tidal fresh segments, SAVH did not have significant correlations with total suspended solids while the other measures did, and PCT_T2 lacked significant correlations with dissolved inorganic phosphorus (Table VII-6). In oligohaline segments, PCT_T2 and PCT_T3 lacked any significant correlations with chlorophyll *a*, while these were found for SAVH. In all segments with significant correlations, the correlations were slightly stronger with SAVH than with the other two parameters. Thus, based on the correlations, there did not seem to be a compelling reason to correct the SAVH variable with the Tier II or Tier III areas, since correlations with SAVH were slightly stronger (Appendix E).

Lagged SAV hectares (the area mapped the following year, LAGSAVH) showed similar correlations with the SAV habitat requirements as were found for SAV area mapped the same year, except for chlorophyll *a* in polyhaline habitats, which was significantly correlated with lagged SAV area but not correlated with SAV area the same year. Most of the significant polyhaline correlations with SAV habitat requirements were slightly higher for lagged SAV area (except for dissolved inorganic phosphorus), compared with SAV area mapped the same year. This tends to support the hypothesis that water quality in the current year affects SAV area in the next year, but the effect was not a dramatic one. Thus, unlagged SAV area (SAVH) seems adequate for most correlative analyses.

Change in SAV hectares (the change from the area this year to the area next year) did not have any significant expected correlations with water quality except for PLL(1+) in mesohaline segments and dissolved inorganic nitrogen in polyhaline segments.

Comparisons of significant correlations with water quality over the whole growing season (Appendix E, tables E-1, 3, 5 and 7) to significant correlations with spring water quality (Appendix E, tables E-2, 4, 6 and 8) showed they differed in the following cases.

Spring correlations were weaker in tidal fresh segments compared to correlations over the whole growing season for total suspended solids and dissolved inorganic phosphorus (the only two parameters that had significant correlations over the whole year in tidal fresh segments). Spring correlations were stronger in oligohaline segments for K_d, PLW, PLL and dissolved inorganic phosphorus and weaker for total suspended solids and chlorophyll *a*. Whole-year correlations were stronger or very similar in mesohaline segments for all but one of the parameters with significant correlations (K_d, PLW, PLL, chlorophyll *a* and dissolved inorganic phosphorus). Spring correlations were slightly stronger for total suspended solids. Spring correlations were weaker in polyhaline segments for K_d, PLW, PLL, dissolved inorganic phosphorus and dissolved inorganic nitrogen. Spring correlations for chlorophyll *a* in polyhaline segments were barely significant, but were not significant over the whole growing season.

Spring correlations were weaker in 12 cases, and stronger in six cases. Thus, there does not seem to be a compelling reason to use spring water quality in SAV habitat requirements in place of water quality over the whole growing season.

Now, as expected, the light parameters (PLL, PLW and K_d) usually had the strongest correlation. In oligohaline segments, total suspended solids, PLW and PLL had the strongest correlations with unlagged SAV area over the whole growing season, while dissolved inorganic phosphorus and total suspended solids had the strongest correlations in tidal fresh segments. In mesohaline and polyhaline segments, PLL, PLW and/or K_d had the strongest correlations with unlagged SAV area over the whole growing season.

Scatter plots for each salinity regime are graphed in figures VII-5 through VII-8 for the four salinity regimes, respectively. PLL(1+) was used on the x-axis in all segments for consistency. PLL had the strongest correlation with SAV area in polyhaline segments, and the third-strongest correlation in oligohaline and mesohaline segments. PLL did not have significant correlations with SAV area in tidal fresh segments. Note the large numbers of segments and years with zero or very low SAV areas in all salinity regimes, which make correlation analysis difficult. However, the general pattern that can be seen is the expected one: more SAV where PLL is higher.

CORRELATING SAV DEPTH WITH MEDIAN WATER QUALITY FOR HABITAT REQUIREMENT PARAMETERS

The same correlations done in the last section using SAV area and water quality medians were repeated using SAV depth by year, in place of SAV area by year. The assumptions in this analysis were that SAV would grow deeper where water quality was better, and shallower where water quality was worse. In general, correlations with light parameters (K_d, PLW and PLL) were expected to be stronger than those with other parameters, since light most directly determines the depth at which SAV can grow. Correlations between SAV depth and water quality were expected to be weaker than those between SAV area and water quality because SAV depth is only available for segments that had some SAV that year. This both reduces the sample size for comparisons with SAV depth and reduces the range in the associated water quality, since generally the worst water quality occurs in segments with no SAV. Both changes reduce the likelihood that there will be statistically significant correlations between SAV depth and water quality.

Factors other than water quality also affect the depth at which SAV grows, however. Some SAV species have a lower light requirement than others (see Chapter III), and thus may be able to grow deeper than others, which could increase the weighted mean SAV depth where those species are dominant. Also, physical factors such as current, tides, sediment and wave action could affect SAV depth distribution (see Chapter VI) independently of water quality.

Methods

Methods are described here briefly; detailed methods for calculating SAV depth and percent of SAV within depth categories are given in Appendix E. SAV polygons for each year were overlaid with depth contours at 0.5, 1 and 2 meters MLLW. The area of SAV within each Chesapeake Bay Program segment that fell within four depth categories was calculated: less than 0.5 meters, 0.5 to 1 meter, 1 to 2 meters or greater than 2 meters deep. For this analysis, the four values of SAV area over depth ranges were divided by the total area to convert them to percentages of the total area in that segment (PCT05, PCT1, PCT2 and PCTGT2) and also to a single weighted mean depth (SAVDEP). Analysis methods used were the same as in the previous section, except that lagged depth and annual change in depth were not examined, and correlations with spring water quality were not examined due to small sample sizes and relatively weak spring correlations in the analyses done above.

Results and Discussion

Spearman rank correlations of percentages of SAV in depth categories and weighted mean SAV depth with SAV habitat requirement parameters are shown in Appendix E, tables E-9 through E-12 for the four salinity regimes. Results are summarized in Table VII-7. For most parameters (K_d, total suspended solids, chlorophyll *a*, dissolved inorganic phosphorus and dissolved inorganic nitrogen), negative correlations were expected because more pollution should yield shallower SAV, and positive correlations were expected for PLW and PLL, since more light should yield deeper SAV. Both expectations are reversed (positive for most, negative for PLW/PLL) for the shallowest depth

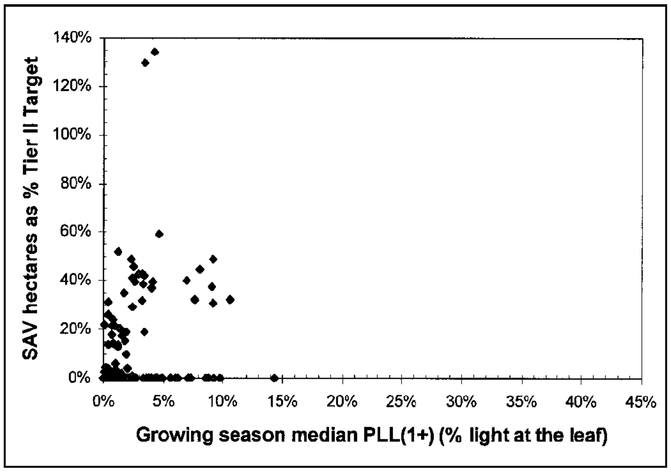

FIGURE VII-5. Tidal Fresh SAV Area vs. Percent Light at the Leaf. Tidal fresh SAV area as a percent of the Tier II SAV distribution restoration target by year and Chesapeake Bay Program segment vs. median percent light at the leaf [PLL(1+)] by year and Chesapeake Bay Program segment, using 1985-1998 data (no data from 1988). Spearman rs = 0.14, N = 124, P = 0.12.

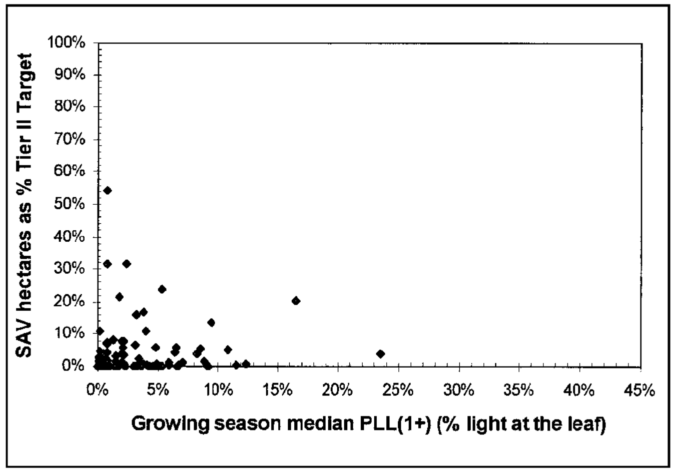

FIGURE VII-6. Oligohaline SAV Area vs. Percent Light at the Leaf. Oligohaline SAV area as a percent of the Tier II SAV distribution restoration target by year and Chesapeake Bay Program segment vs. median percent light at the leaf [PLL(1+)] by year and Chesapeake Bay Program segment, using 1985-1998 data (no data from 1988). Spearman rs = 0.37, N = 182, P = 0.0001.

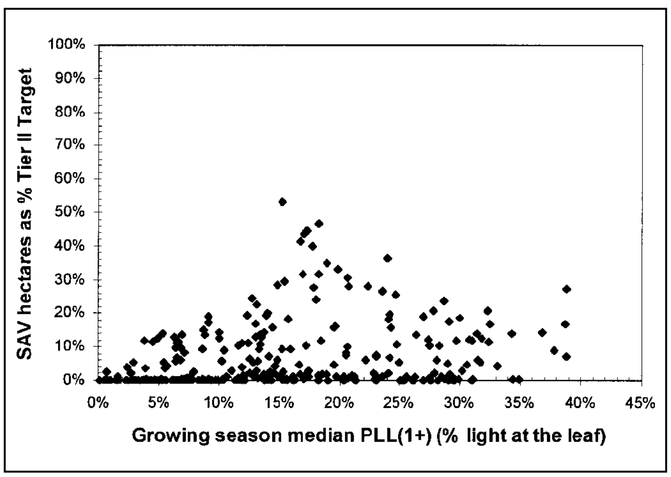

FIGURE VII-7. Mesohaline SAV Area vs. Percent Light at the Leaf Mesohaline SAV area as a percent of the Tier II SAV distribution restoration target by year and Chesapeake Bay Program segment vs. median percent light at the leaf [PLL(1+)] by year and Chesapeake Bay Program segment, using 1985-1998 data (no data from 1988). Spearman rs = 0.51, N = 326, P = 0.0001.

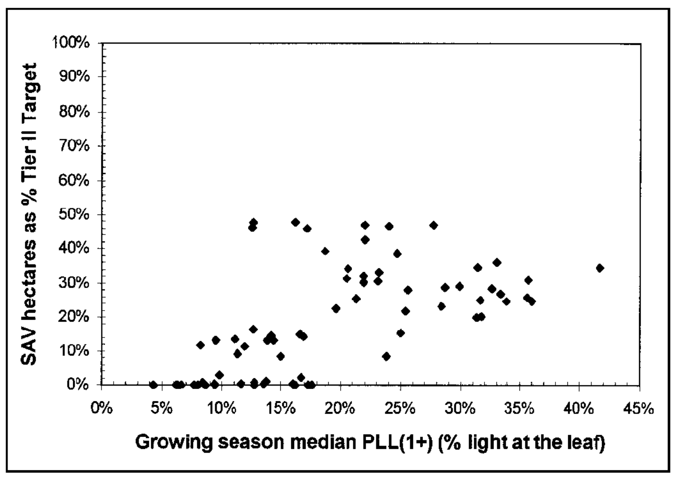

FIGURE VII-8. Polyhaline SAV Area vs. Percent Light at the Leaf. Polyhaline SAV area as a percent of the Tier II SAV distribution restoration target by year and Chesapeake Bay Program segment vs. median percent light at the leaf [PLL(1+)] by year and Chesapeake Bay Program segment, using 1985-1998 data (no data from 1988). Spearman rs = 0.50, N = 60, P = 0.0001.

TABLE VII-7. Salinity regimes that had statistically significant ($P < 0.05$) Spearman rank correlation coefficients in expected directions, between water quality parameters from Chesapeake Bay Program mid-channel water quality stations and measures of SAV depth over Chesapeake Bay Program segments (see Appendix E, tables E-9 through E-12 for correlations, P values and sample sizes), using data from whole growing season.

Water quality parameter	SAV depth parameter				
	SAVDEP	**PCT05**	**PCT1**	**PCT2**	**PCTGT2**
K_d	TF	TF	**TF**	TF	TF
	OH	OH	OH	OH	OH
				MH	MH
	PH	PH	PH		PH
PLW(1+)	TF	TF	**TF**	TF	TF
	OH	OH	OH	OH	OH
				MH	MH
	PH	PH	**PH**		
PLL(1+)	**TF**	TF	**TF**	TF	TF
	OH	OH	OH	OH	OH
				MH	MH
	PH	**PH**	**PH**		PH
TSS	TF	TF	**TF**	TF	TF
	OH	**OH**	**OH**	**OH**	OH
CHLA		TF	**TF**		
	OH	OH	OH	OH	OH
	MH	MH	MH	MH	
DIP	MH	MH	MH	MH	
	PH	PH	PH	PH	**PH**
DIN	MH	MH	MH	MH	MH
	PH	PH	PH	**PH**	PH

KEY: SAV area that fell within four depth categories: less than 0.5 meters, 0.5 to 1 meter, 1 to 2 meters or greater than 2 meters deep, was mapped, and each area was divided by the total area over all four ranges to convert them to percentages of the total area in that segment (PCT05, PCT1, PCT2 and PCTGT2, respectively) and also to a single weighted mean depth (SAVDEP).
TF = tidal fresh, OH = oligohaline, MH = mesohaline, and PH= polyhaline (see Table VII-1 for salinities).
Light attenuation coefficient = K_d; percent light through water = PLW; percent light at the leaf = PLL; total suspended solids = TSS; chlorophyll *a* = CHLA; dissolved inorganic phosphorus = DIP; and dissolved inorganic nitrogen = DIN.
Regimes in bold had correlations >+/- 0.5 over the whole growing season.

category, PCT05, since SAV is expected to be more common in the shallowest depths when conditions are worse because it cannot grow in deeper water.

Table VII-7 shows that, as expected, most of the light parameters showed significant correlations with SAV depth parameters in the expected directions, except with some depth parameters in mesohaline and polyhaline areas. In mesohaline areas, significant correlations were found with the deeper percentages only (PCT2 and PCTGT2), and in polyhaline areas, significant correlations were found with the shallower depths and the weighted mean depth only (SAVDEP, PCT05, and PCT1). Reasons for these differences are not known.

In examining correlations with the other water quality parameters two patterns were seen. Correlations with total suspended solids and chlorophyll *a* were stronger in tidal fresh and oligohaline segments, while correlations with nutrients were stronger in mesohaline and polyhaline segments. Most of the correlations with total suspended solids and chlorophyll *a* were significant and in the expected directions in tidal fresh and oligohaline segments, suggesting that they may affect depth distributions along with light in lower salinity areas. In mesohaline segments, only chlorophyll *a* had significant correlations in the expected direction, and in polyhaline segments, there were no significant correlations with total suspended solids or chlorophyll *a*. In tidal fresh and oligohaline areas, all of the correlations between nutrients (dissolved inorganic phosphorus and dissolved inorganic nitrogen) and depth parameters were either significant but in the wrong direction, or not significant. This was expected for dissolved inorganic nitrogen, since there is no habitat requirement for dissolved inorganic nitrogen in the two lower salinity regimes. In mesohaline and tidal fresh segments, all but one of the correlations with dissolved inorganic phosphorus and dissolved inorganic nitrogen were significant and in the expected directions.

CONCLUSIONS

Comparisons of SAV area or depth to water quality should always be done for salinity regimes separately. None of the detailed relationships were consistent across all salinity regimes.

In general, segments with median water quality better than the SAV habitat requirements had some SAV, while those with medians worse than the requirements had less or no SAV. SAV also tended to grow at deeper depths where water quality was better, and at shallower depths where water quality was worse. This provides empirical confirmation of the light requirements that were determined from research and ecological modeling.

Segments that failed the minimum light requirement in half of the past six years or more were identified and their SAV area checked. There were two segments with more than 35 hectares of SAV in 1997 that failed PLL at $Z = 0.25$ plus half the tidal range or less. In both cases, there were reasons why SAV could be growing there even though monitoring data showed the minimum light requirement was usually failed.

In the polyhaline regime, PLL was a better predictor of SAV area and SAV depth than PLW, when there was a significant relationship with SAV area. In other salinity regimes, PLL and PLW were very similar as predictors, except in oligohaline segments, where PLW was a slightly better predictor than PLL of SAV area and depth.

PLL or PLW were often, but not always, the strongest predictors of SAV area among all the SAV habitat requirements. However, given the highly skewed distribution of SAV area data and differences in percent light levels, these results are not really a test of the usefulness of these parameters.

In some cases, in all four salinity regimes, water quality showed slightly stronger correlations with the SAV area mapped in the following year, compared to correlations with SAV area in the current year. However, the improvement with lagged SAV area did not appear to be consistent enough or large enough to warrant using the latter when calculating correlations with water quality data, especially since lagging drops a year off the sample size.

Spring median water quality did not appear to be consistently better than growing season median water quality in predicting SAV area, and in many cases (especially in polyhaline segments) it was a worse predictor. Thus, we recommend using water quality data over the whole growing season to assess attainment of the SAV habitat requirements.

One or more of the three light parameters (K_d, PLW and/or PLL) usually were the best predictors of SAV depth over most depth categories. In oligohaline segments, chlorophyll *a* had slightly stronger correlations in three depth categories, and in polyhaline segments, dissolved inorganic nitrogen and dissolved inorganic phosphorus had stronger correlations than light with the percent of SAV area in the two deeper categories. Dissolved inorganic nitrogen and dissolved inorganic phosphorus were also the strongest predictors of SAV area in polyhaline segments.

Chesapeake Bay Program midchannel water quality monitoring data often show the expected patterns in analyses that compare SAV area and depth with water quality, even though the stations are not located next to SAV beds. This supports the continued use of these data to assess attainment of SAV habitat requirements. However, care must be taken to omit data from some stations where the SAV is in a different water body from the monitoring stations (such as Little Creek in segment CB8PH). In these cases, additional water quality monitoring data from sites near the SAV beds are needed.

CHAPTER **VIII**

Chesapeake Bay SAV Distribution Restoration Goals and Targets

The original tiered SAV distribution restoration targets for Chesapeake Bay were first published in the 1992 SAV technical synthesis in response to commitments set forth in the *Submerged Aquatic Vegetation Policy for the Chesapeake Bay and Tidal Tributaries* (Chesapeake Executive Council 1989). The Tier I SAV distribution restoration target is the restoration of SAV to areas currently or previously inhabited by SAV as mapped through regional and baywide aerial surveys from 1971 through 1990 (Batiuk *et al.* 1992; Dennison *et al.* 1993). The Tier II and Tier III distribution restoration targets are the restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat, down to the 1- and 2-meter depth contours, respectively.

Baywide and Chesapeake Bay Program segment-based target acreages were published in 1992 for the Tier I and Tier III restoration targets (Batiuk *et al.* 1992). The lack of sufficient Bay bottom bathymetry data to create a 1-meter depth contour prevented delineation of the Tier II restoration target at that time. In 1993 the Chesapeake Executive Council formally adopted the Tier I SAV distribution restoration target as the Chesapeake Bay Program's first quantitative living resource restoration goal (Chesapeake Executive Council 1993). The refined baywide and regional SAV distribution restoration goals and targets presented here are critical in assessing the success of efforts to restore SAV in Chesapeake Bay and its tidal tributaries.

DISTRIBUTION TARGETS DEVELOPMENT APPROACH

The tiered Chesapeake Bay SAV distribution restoration targets were originally developed in 1992 by mapping potential SAV habitat on U.S. Geological Survey (USGS) quadrangles; removing shallow water habitat areas where SAV were not expected to revegetate; and comparing these areas with historical survey data and the most current distribution data. Composite SAV maps were plotted by USGS quadrangles from all available computerized digital SAV bed data from Chesapeake Bay aerial surveys from 1971 through 1990. The 1- and 2-meter depth contours at mean low water (MLW) were digitized from National Oceanic Atmospheric Administration (NOAA) bathymetry maps. Because the NOAA bathymetry maps are relatively inaccurate in small tidal creeks and rivers where depth contours generally were not present, an overestimate of an area within a certain depth contour can occur. These maps were overlaid at the 1:24,000 scale to produce composite maps of known and documented SAV distribution since the early 1970s, with the outline of potential SAV habitat initially defined by the 1- and 2-meter depth contours.

Potential habitat was initially defined as all shoal areas of Chesapeake Bay and tributaries less than 2 meters. Although historically SAV in Chesapeake Bay probably grew down to depths of 3 meters or more, the 2-meter depth contour was chosen because it was the best compromise of the anticipated maximum depth penetration of most SAV species. For several SAV species (notably *Myriophyllum spicatum* and *Hydrilla verticillata*), maximum depth penetration might be greater than 2 meters, but it was felt that this would be an exception.

Areas that were highly unlikely to support SAV were annotated on the composite maps. Criteria for excluding certain areas from the maps were based primarily on habitat areas exposed to high wave energy and that have undergone physical modifications that prevented them from supporting SAV growth. The absence of documentation on the historical presence of SAV in a certain region of a tributary, embayment or the mainstem was not used as a reason to delineate and exclude the shallow water habitats in these regions as unlikely to support future SAV growth. For example, some areas that have not supported SAV in the recent past (such as the tidal fresh and oligohaline areas of the James, York and Rappahannock rivers) were included in the distribution restoration targets. This distinction was based on the following assumption: since the upper Potomac River near Washington, D.C. supported these stands of SAV in the early 1900s (Cumming *et al.* 1916), there should be no reason to assume that SAV was not present in similar areas in the tidal fresh and oligohaline reaches of other river systems in Chesapeake Bay. The anecdotal evidence from disparate regions of the Bay, as well as aerial photographic evidence for some areas in the 1930s, indicate the major areas where SAV grew in the early part of the 20th century. In addition, many small tidal creeks in tidal fresh and oligohaline areas throughout the Bay and its tidal tributaries today contain small pockets of a variety of SAV species. It is assumed that these are the last remnants of what were once large expansive stands in earlier periods in the upper sections of these tributaries. The seed and pollen records (Brush and Hilgartner 1989) support the line of evidence that SAV was once significantly more abundant than it is today.

The areas annotated as highly unlikely to support SAV were digitized and deleted from the ARC/INFO files of potential SAV habitat delineated by the 2-meter depth contour. A second level of habitat restriction was considered in those areas where SAV was presently found or had the potential to grow in the 2-meter contour. This habitat restriction was considered in areas where wave exposure is highly likely to prevent SAV from growing down 2 meters in depth but would be dampened enough to allow SAV to grow closer inshore (less than 1 meter). Assessment of areas that would fall into this category was based on the same criteria used to generate the composite maps for the 2-meter restricted areas. The complete, detailed description of the original process for developing the tiered restoration goals and targets is found on pages 109-119 in Batiuk *et al.* (1992).

TIERED SAV DISTRIBUTION RESTORATION GOALS AND TARGETS

To provide incremental measures of progress, a tiered set of SAV distribution restoration targets have been established for Chesapeake Bay. Each target represents expansions in SAV distribution that are anticipated in response to improvements in water quality. These water quality improvements will be measured as achievement of the minimum light requirements at 1- and 2-meter restoration depths. Progress toward the SAV distribution restoration targets will continue to be measured through the annual Chesapeake Bay SAV Aerial Survey Monitoring Program.

Refinements have been made to the Tier I restoration goal as a result of a reevaluation of the historical SAV aerial survey digital data sets, including a thorough quality assurance evaluation, which resulted in corrections to the original data. The revised Tier I restoration goal areas are presented by Chesapeake Bay Program segments in Table VIII-1 and illustrated in Figure VIII-1.

The Tier II SAV distribution restoration target is the restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat down to the 1-meter depth contour. Building from the recent completion of a synthesis of all available Bay bathymetry data (Chesapeake Bay Program 1997), a 1-meter depth contour along the entire Chesapeake Bay and tidal tributaries shoreline was developed. The Tier II target includes all areas of past SAV habitat delineated in the Tier I goal, as well as shallow water habitats delineated within this 1-meter depth contour (Figure VIII-2; Table VIII-1). Tier II excludes areas where SAV is considered unlikely to survive and grow due to the direct and indirect adverse effects of high wave action. These "exclusion zones" used for the Tier II and Tier III targets described here were the same ones used in defining Tier III areas in Batiuk *et al.* (1992).

The Tier III SAV distribution restoration target is the restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat down to the 2-meter depth contour. A new 2-meter depth contour along the entire tidal Bay shoreline was developed through contouring the expanded Bay bottom bathymetry database. The revised Tier III target includes all areas in the Tier I goal and Tier II target, as well as shallow water habitats delineated within this new 2-meter depth contour (Figure VIII-3; Table VIII-1). The Tier III target excludes areas where SAV is considered unlikely to survive and grow due to the direct and indirect adverse effects of high wave action. Figure VIII-4 illustrates the Chesapeake Bay Program Segmentation Scheme, and Table VIII-2 provides the tiered SAV distribution restoration goals and targets in terms of hectares.

TABLE VIII-1. Chesapeake Bay SAV distribution restoration Tier I goal, and tiers II and III targets by Chesapeake Bay Program segment in acres.

CBP Segment	Chesapeake Bay Program Segment Name	Tier I Goal	Tier II Target	Tier III Target
CB1TF	Northern Chesapeake Bay	7,690	13,714	20,401
NORTF	Northeast River	20	934	2,743
ELKOH	Elk River	1,105	2,785	5,028
C&DOH	Chesapeake & Delaware Canal	2	124	170
BOHOH	Bohemia River	42	1,132	1,905
SASOH	Sassafras River	408	2,614	3,699
CB2OH	Upper Chesapeake Bay	660	5,439	9,212
CB3MH	Upper Central Chesapeake Bay	1,725	4,702	5,510
BSHOH	Bush River	57	2,068	4,606
GUNOH	Gunpowder River	865	2,896	7,460
MIDOH	Middle River	860	1,431	2,481
BACOH	Back River	0	1,302	2,861
PATMH	Patapsco River	124	1,984	3,543
CHSMH	Lower Chester River	3,751	6,990	11,510
CHSOH	Middle Chester River	0	1,663	2,310
CHSTF	Upper Chester River	0	766	870
MAGMH	Magothy River	586	1,500	2,177
SEVMH	Severn River	465	1,347	2,108
SOUMH	South River	52	1,485	2,288
RHDMH	Rhode River	15	623	904
WSTMH	West River	116	1,092	1,527
EASMH	Eastern Bay	6,126	13,091	20,808
CB4MH	Middle Central Chesapeake Bay	376	7,949	9,301
CHOMH1	Mouth of the Choptank River	7,388	12,968	18,424
CHOMH2	Lower Choptank River	462	3,771	6,222
CHOOH	Middle Choptank River	0	852	1,285
CHOTF	Upper Choptank River	0	0	0
LCHMH	Little Choptank River	1,522	8,102	11,799
PAXMH	Lower Patuxent River	356	5,155	8,829
PAXOH	Middle Patuxent River	2	1,436	2,073
PAXTF	Upper Patuxent River	15	504	707
WBRTF	Western Branch of the Patuxent River	0	32	32
HNGMH	Honga River	3,951	10,645	15,481
FSBMH	Fishing Bay	32	6,939	13,633
NANMH	Lower Nanticoke River	0	3,188	7,714
NANOH	Middle Nanticoke River	0	1,522	2,056
NANTF	Upper Nanticoke River	0	598	887
WICMH	Wicomico River	0	3,442	6,385
MANMH	Manokin River	682	6,336	9,338

continued

TABLE VIII-1. Chesapeake Bay SAV distribution restoration Tier I goal, and tiers II and III targets by Chesapeake Bay Program segment in acres (*continued*)

CBP Segment	Chesapeake Bay Program Segment Name	Tier I Goal	Tier II Target	Tier III Target
BIGMH	Big Annemessex River	902	3,197	5,068
POCMH	Lower Pocomoke River	2,078	14,016	17,969
POCOH	Middle Pocomoke River	0	1,406	1,515
POCTF	Upper Pocomoke River	0	581	749
TANMH	Tangier Sound	19,899	38,874	58,024
POTMH	Lower Potomac River	988	26,069	45,807
POTOH	Middle Potomac River	4,265	7,188	15,199
POTTF	Upper Potomac River	6,405	7,794	17,838
MATTF	Mattawoman Creek	133	697	1,389
PISTF	Piscataway Creek	835	588	914
CB5MH	Lower Central Chesapeake Bay	4,776	15,021	18,691
RPPMH	Lower Rappahannock River	2,471	19,770	30,035
CRRMH	Corrotoman River	541	1,819	2,612
RPPOH	Middle Rappahannock River	0	1,653	2,511
RPPTF	Upper Rappahannock River	0	3,190	4,515
PIAMH	Piankatank River	1,994	5,668	7,789
CB6PH	Western Lower Chesapeake Bay	1,265	3,936	5,130
CB7PH	Eastern Lower Chesapeake Bay	12,081	28,510	32,575
MOBPH	Mobjack Bay	13,744	22,978	30,554
YRKMH	Lower York River	54	8,387	12,666
YRKPH	Middle York River	1,401	5,088	7,139
MPNOH	Lower Mattaponi River	0	445	613
MPNTF	Upper Mattaponi River	0	996	1,352
PMKOH	Lower Pumunkey River	0	598	860
PMKTF	Upper Pumunkey River	0	2,187	2,654
JMSPH	Mouth of the James River	40	1,616	2,266
ELIPH	Mouth of the Elizabeth River	0	0	0
LAFMH	Lafayette River	0	0	0
ELIMH	Middle Elizabeth River	0	0	0
EBEMH	Eastern Branch of the Elizabeth River	0	0	0
SBEMH	South Branch of the Elizabeth River	0	0	0
WBEMH	Western Branch of the Elizabeth River	0	0	0
JMSMH	Lower James River	0	17,613	29,138
JMSOH	Middle James River	0	6,476	10,954
CHKOH	Chickahominy River	225	3,506	4,505
JMSTF	Upper James River	0	10,400	12,842
APPTF	Appomattox River	0	1,307	1,604
LYNPH	Lynhaven & Back Bays	175	3,304	3,961
CB8PH	Mouth of the Chesapeake Bay	0	697	1,053
TOTAL	Chesapeake Bay	113,720	408,689	618,773

TABLE VIII-2. Chesapeake Bay SAV distribution restoration Tier I goal, and tiers II and III targets by Chesapeake Bay Program segment in hectares.

CBP Segment	Chesapeake Bay Program Segment Name	Tier I Goal	Tier II Target	Tier III Target
CB1TF	Northern Chesapeake Bay	3,112	5,550	8,256
NORTF	Northeast River	8	378	1,110
ELKOH	Elk River	447	1,127	2,035
C&DOH	Chesapeake & Delaware Canal	1	50	69
BOHOH	Bohemia River	17	458	771
SASOH	Sassafras River	165	1,058	1,497
CB2OH	Upper Chesapeake Bay	267	2,201	3,728
CB3MH	Upper Central Chesapeake Bay	698	1,903	2,230
BSHOH	Bush River	23	837	1,864
GUNOH	Gunpowder River	350	1,172	3,019
MIDOH	Middle River	348	579	1,004
BACOH	Back River	0	527	1,158
PATMH	Patapsco River	50	803	1,434
CHSMH	Lower Chester River	1,518	2,829	4,658
CHSOH	Middle Chester River	0	673	935
CHSTF	Upper Chester River	0	310	352
MAGMH	Magothy River	237	607	881
SEVMH	Severn River	188	545	853
SOUMH	South River	21	601	926
RHDMH	Rhode River	6	252	366
WSTMH	West River	47	442	618
EASMH	Eastern Bay	2,479	5,298	8,421
CB4MH	Middle Central Chesapeake Bay	152	3,217	3,764
CHOMH1	Mouth of the Choptank River	2,990	5,248	7,456
CHOMH2	Lower Choptank River	187	1,526	2,518
CHOOH	Middle Choptank River	0	345	520
CHOTF	Upper Choptank River	0	0	0
LCHMH	Little Choptank River	616	3,279	4,775
PAXMH	Lower Patuxent River	144	2,086	3,573
PAXOH	Middle Patuxent River	1	581	839
PAXTF	Upper Patuxent River	6	204	286
WBRTF	Western Branch of the Patuxent River	0	13	13
HNGMH	Honga River	1,599	4,308	6,265
FSBMH	Fishing Bay	13	2,808	5,517
NANMH	Lower Nanticoke River	0	1,290	3,122
NANOH	Middle Nanticoke River	0	616	832
NANTF	Upper Nanticoke River	0	242	359
WICMH	Wicomico River	0	1,393	2,584
MANMH	Manokin River	276	2,564	3,779

continued

TABLE VIII-2. Chesapeake Bay SAV distribution restoration Tier I goal, and tiers II and III targets by Chesapeake Bay Program segment in hectares (*continued*)

CBP Segment	Chesapeake Bay Program Segment Name	Tier I Goal	Tier II Target	Tier III Target
BIGMH	Big Annemessex River	365	1,294	2,051
POCMH	Lower Pocomoke River	841	5,672	7,272
POCOH	Middle Pocomoke River	0	569	613
POCTF	Upper Pocomoke River	0	235	303
TANMH	Tangier Sound	8,053	15,732	23,482
POTMH	Lower Potomac River	400	10,550	18,538
POTOH	Middle Potomac River	1,726	2,909	6,151
POTTF	Upper Potomac River	2,592	3,154	7,219
MATTF	Mattawoman Creek	54	282	562
PISTF	Piscataway Creek	338	238	370
CB5MH	Lower Central Chesapeake Bay	1,933	6,079	7,564
RPPMH	Lower Rappahannock River	1,000	8,001	12,155
CRRMH	Corrotoman River	219	736	1,057
RPPOH	Middle Rappahannock River	0	669	1,016
RPPTF	Upper Rappahannock River	0	1,291	1,827
PIAMH	Piankatank River	807	2,294	3,152
CB6PH	Western Lower Chesapeake Bay	512	1,593	2,076
CB7PH	Eastern Lower Chesapeake Bay	4,889	11,538	13,183
MOBPH	Mobjack Bay	5,562	9,299	12,365
YRKMH	Lower York River	22	3,394	5,126
YRKPH	Middle York River	567	2,059	2,889
MPNOH	Lower Mattaponi River	0	180	248
MPNTF	Upper Mattaponi River	0	403	547
PMKOH	Lower Pumunkey River	0	242	348
PMKTF	Upper Pumunkey River	0	885	1,074
JMSPH	Mouth of the James River	16	654	917
ELIPH	Mouth of the Elizabeth River	0	0	0
LAFMH	Lafayette River	0	0	0
ELIMH	Middle Elizabeth River	0	0	0
EBEMH	Eastern Branch of the Elizabeth River	0	0	0
SBEMH	South Branch of the Elizabeth River	0	0	0
WBEMH	Western Branch of the Elizabeth River	0	0	0
JMSMH	Lower James River	0	7,128	11,792
JMSOH	Middle James River	0	2,621	4,433
CHKOH	Chickahominy River	91	1,419	1,823
JMSTF	Upper James River	0	4,209	5,197
APPTF	Appomattox River	0	529	649
LYNPH	Lynhaven & Back Bays	71	1,337	1,603
CB8PH	Mouth of the Chesapeake Bay	0	282	426
TOTAL	Chesapeake Bay	46,022	165,394	250,414

Figure VIII-1. Tier I SAV Distribution Restoration Goal.

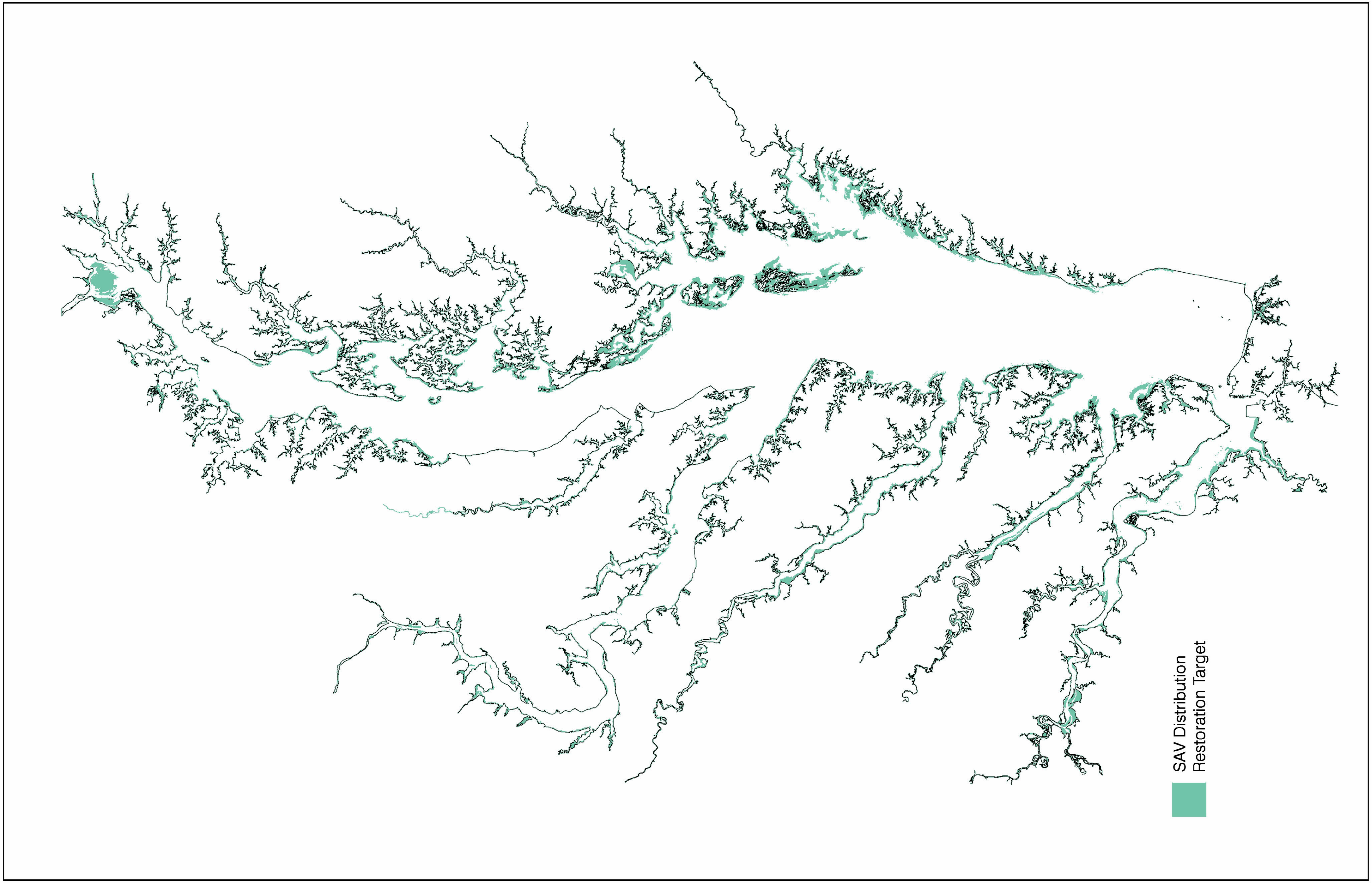

Figure VIII-2. Tier II SAV Distribution Restoration Target.

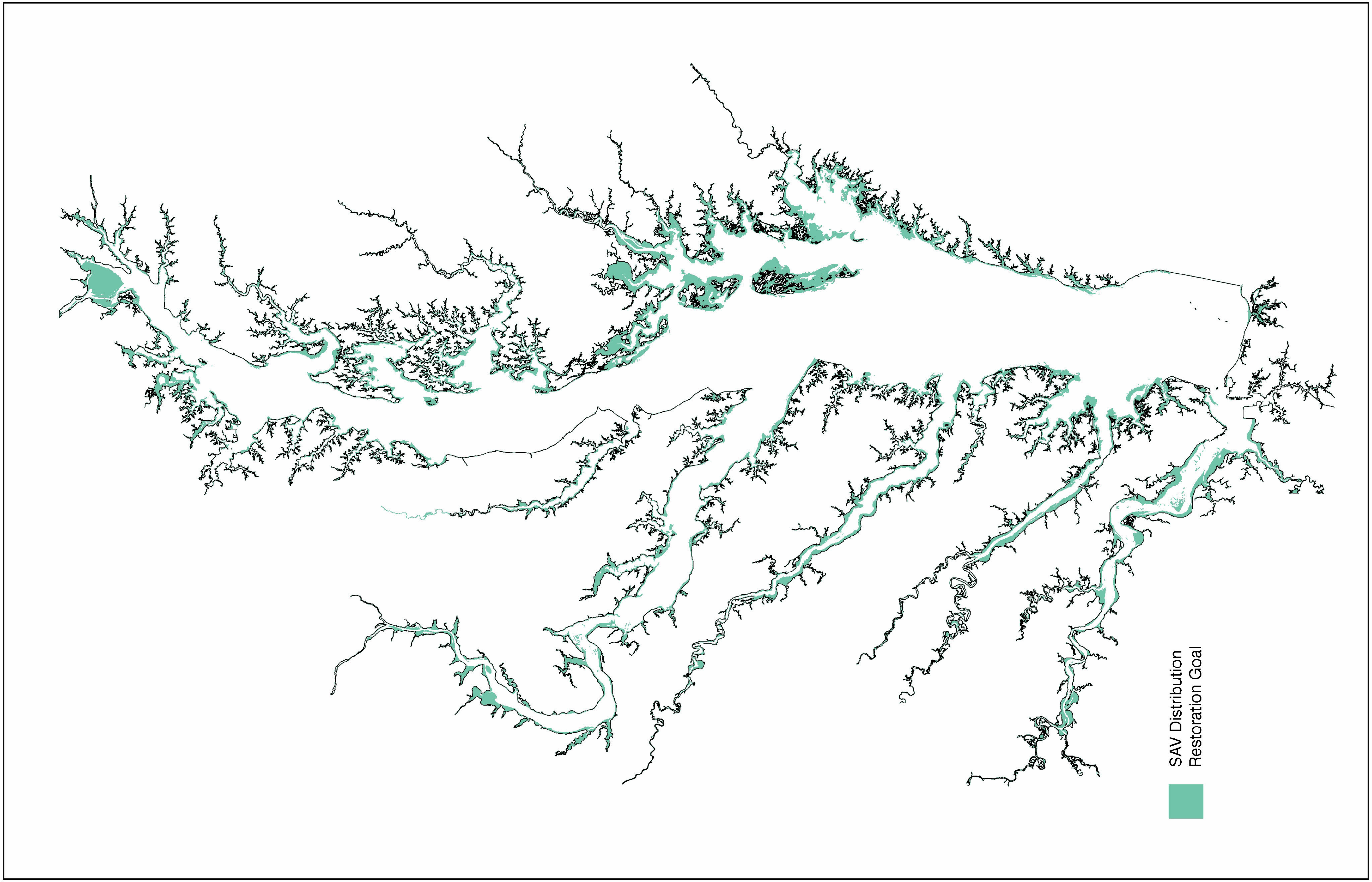

Figure VIII-3. Tier III SAV Distribution Restoration Goal.

Figure VIII-4. Chesapeake Bay Program Segmentation Scheme.

CHAPTER IX

Comparing Nearshore and Midchannel Water Quality Conditions

In the Chesapeake Bay region, most governmental agency tidal water quality monitoring programs sample only midchannel locations to reduce sampling time and costs. This provides crucial water quality information for determining status and long-term trends of the Chesapeake Bay mainstem, its tidal tributaries and embayments. However, does midchannel monitoring provide adequate information to characterize the status of biologically important nearshore areas? If the nearshore values are found to be statistically similar to the midchannel values, then resource managers could make better informed decisions about nearshore areas without requiring additional water quality monitoring locations. Conversely, differing nearshore and midchannel conditions might require revision of existing monitoring programs or the initiation of new ones.

Several studies have addressed the nearshore vs. midchannel sampling issue in Chesapeake Bay (Table IX-1; Stevenson *et al.* 1991; Batiuk *et al.* 1992; Chesapeake Bay Program 1993; Ruffin 1995; Bergstrom, unpublished data; Parham 1996). While most studies indicate that midchannel data can be used to describe nearshore conditions, several suggest the opposite. There is no doubt that demonstrable differences in water quality can occur between nearshore and midchannel stations over varying temporal and spatial scales, especially when submerged aquatic vegetation is present (Ward *et al.* 1984; Moore *et al.* 1995; Moore 1996). Other possible causes of variability between nearshore and midchannel environments include localized resuspension of sediments, algal patchiness, point source effluents or sediment chemistry variability (Goldsborough and Kemp 1988; Moore 1996).

The findings presented in this chapter result from a comprehensive analysis of directly accessible nearshore and midchannel data in the Chesapeake Bay collected since 1983, to determine whether midchannel water quality monitoring data are applicable for characterizing nearshore environments. The full report describing these analyses has been published by Karrh (1999). Data for this study were incorporated from all over Chesapeake Bay and its tidal tributaries, including the upper Chesapeake Bay region; the Middle, Magothy, Rhode, Chester, Choptank, Patuxent, Potomac, Rappahanock, Poquoson, York and James rivers; and Mobjack Bay. Data were obtained from state monitoring efforts, academic researchers and citizen monitors. Most data used in the analyses came from unvegetated areas.

METHODS

The parameters analyzed included Secchi depth, dissolved inorganic nitrogen, dissolved inorganic phosphorous, chlorophyll *a*, total suspended solids and salinity. These are the parameters most relevant to the survival of submerged aquatic vegetation (Batiuk *et al.* 1992; Dennison *et al.* 1993). Salinity was also included as a diagnostic parameter in assessing the comparability of sites. The study period was limited to the SAV growing season (April to October in tidal fresh, oligohaline and mesohaline areas and March to May and September to November in polyhaline areas). In some datasets, it was necessary to sum the nitrite, nitrate and ammonia fractions to obtain dissolved inorganic nitrogen and to convert data to similar units in all datasets. Since many of the citizen monitoring datasets

TABLE IX-1. Summary of previous nearshore/midchannel comparisons. Area indicates tidal tributary or mainstem Chesapeake Bay study area. Source indicates publication that the results appear in. Under K_d (light attenuation coefficient), DIN (dissolved inorganic nitrogen), DIP (dissolved inorganic phosphorous), TSS (total suspended solids) and chlorophyll *a*, the results are shown for each study, based upon whether the midchannel data can be used to characterize the nearshore environment. Yes = midchannel data can be applied to the nearshore areas, No = cannot be used and ND = no data.

Area	Source	K_d	DIN	DIP	TSS	Chlorophyll *a*
Upper Bay	Batiuk *et al.* 1992	Yes	Yes	Yes	Yes	Yes
Chester	Ruffin 1996	No	ND	ND	ND	ND
Choptank	Batiuk *et al.* 1992	Yes	Yes	Yes	Yes	Yes
Choptank	Stevenson *et al.* 1991	No*	No*	No*	No*	No*
Choptank	Parham 1996	Yes	ND	ND	ND	ND
Patuxent	Bergstrom unpublished	ND	Yes	Yes	ND	ND
Patuxent	Parham 1996	Yes	ND	ND	ND	ND
Potomac	Batiuk *et al.* 1992	Yes	Yes	Yes	Yes	Yes
York	Batiuk *et al.* 1992	Yes	Yes	Yes	Yes	Yes
Mainstem Bay	Chesapeake Bay Program 1993	No	Yes	Yes	Yes	Yes

*** The authors of this study concluded that the wide variation in the data was masking any potential significant statistical result, therefore they based their conclusions on their correlational analyses.**

report Secchi depth and not K_d, K_d values given in some datasets were converted to Secchi depth using the appropriate conversion factor (see Chapter III; Batiuk *et al.* 1992).

Data Sources

Data for this study were obtained from many sources. Only datasets with two or more years were used for the analysis. Citizen monitoring data were from the Alliance for the Chesapeake Bay, the Magothy River Association and the Anne Arundel County Volunteer Monitoring Program. Nearshore water quality data used in this analysis were obtained from George Mason University, the University of Maryland, the Virginia Institute of Marine Science, the Smithsonian Environmental Research Center and Harford Community College. Midchannel water quality data were synthesized from monitoring programs run by the Maryland Department of the Environment, the Maryland Department of Natural Resources, the Virginia Department of Environmental Quality and the U.S. Geological Survey. All data have been placed into SAS datasets for analysis and are directly accessible through the Chesapeake Bay Program web site at www.chesapeakebay.net.

Station Selection

The stations used in the comparisons were selected through the use of ArcView© desktop GIS software to create maps showing the positions of the stations

(Figure IX-1). As most of the nearshore stations were established for other purposes than a nearshore/midchannel comparison, stations were picked for comparison based solely on their proximity to one another, and to maximize the number of possible comparisons.

Stations compared were located less than 10 kilometers apart, with most paired stations less than five kilometers apart. The spatial relationship of stations to one another was considered, so that a nearshore station located far up a subtributary was not paired with a midchannel station in the tributary's mainstem. In this way, the stations did not differ dramatically in chemical or physical nature. The distances between paired stations were determined, allowing conclusions to be drawn on how far away from a given midchannel station the nearshore water quality conditions can still be characterized using midchannel data.

Statistical Analysis

Individual nearshore/midchannel data were analyzed using the Wilcoxon paired-sample test (Wilcoxon 1945; Zar 1984). This test examines differences between two samples of the same observation (i.e., one nearshore vs. one midchannel station sampled on the same day). The actual daily values were used, not a median. If all of the samples from the two stations being compared had approximately the same number and magnitude of positive and negative differences, then the stations were considered similar in respect to the parameter of interest. However, if one station had a consistently higher or lower value than the other, then the stations were considered significantly different with respect to the parameter of interest.

The Wilcoxon paired-sample test is a nonparametric analog to the paired-sample t-test, and is more appropriate to water quality data where the data cannot be assumed to be normally distributed. The Wilcoxon paired-sample test is 95 percent as powerful in detecting differences between two sets of data as the t-test. Significance was evaluated at an level of .05. The tests were performed using a SAS program. For the purposes of this report, the term, "comparison" refers to a station A vs. station B statistical analysis. Figures IX-2 and IX-3 show example box and scatter plots for the York River, along with the results of the statistical analyses. A complete set of similar figures for all the nearshore/midchannel paired station comparisons are published in Karrh (1999).

In order to perform the Wilcoxon test, the data from two stations must have paired observations. Since many of the stations were sampled on different dates, the data were forced to match by date. A 10-day sampling difference was used as the limit to keep temporal differences between stations to a minimum while maximizing the number of paired stations for the comparison. Most of the temporal differences were one to five days.

Ideally, the stations compared would have data collected within hours of one another. However, the data used in this study were obtained from a variety of sources, each with different sampling schedules and protocols. In order to have sufficient observations to perform some of the comparisons, it was necessary to be fairly pragmatic about temporal differences. The analyses were conducted using all available data for all years. It has been argued that the data should be analyzed by year to account for interannual water quality variability. However, the goal of this study was to determine if midchannel data are applicable to nearshore conditions overall. For example, if a six-year dataset was analyzed by year for a parameter and there were three significant and three nonsignificant results, are these stations comparable or are they different?

RESULTS AND DISCUSSION

The results of this comprehensive study show that applicability of midchannel data to nearshore environments is very site-specific. There are wide variations in the results within tributaries and between comparisons using one midchannel station vs. multiple nearshore stations. Karrh (1999) describes the site-specific nature of the results in more depth. Possible causes of this variability include localized resuspension of sediments, algal patchiness, point source effluents or sediment chemistry variability. Also, differences in sampling schedule and protocols between midchannel and nearshore sampling programs could contribute to observed differences. Another confounding factor may be the presence of SAV at certain sites, as the plants can change total suspended solids, dissolved inorganic nitrogen, dissolved inorganic phosphorus, chlorophyll *a* concentrations and light penetration locally.

Table IX-2 summarizes the results of the statistical analyses by tributary, expressed as the percentage of the total number of comparisons that yielded a nonsignificant result (i.e., the nearshore and midchannel stations

FIGURE IX-1. Nearshore and Midchannel Water Quality Monitoring Stations. Chesapeake Bay and tidal tributary water quality monitoring stations used in the nearshore vs. midchannel analyses.

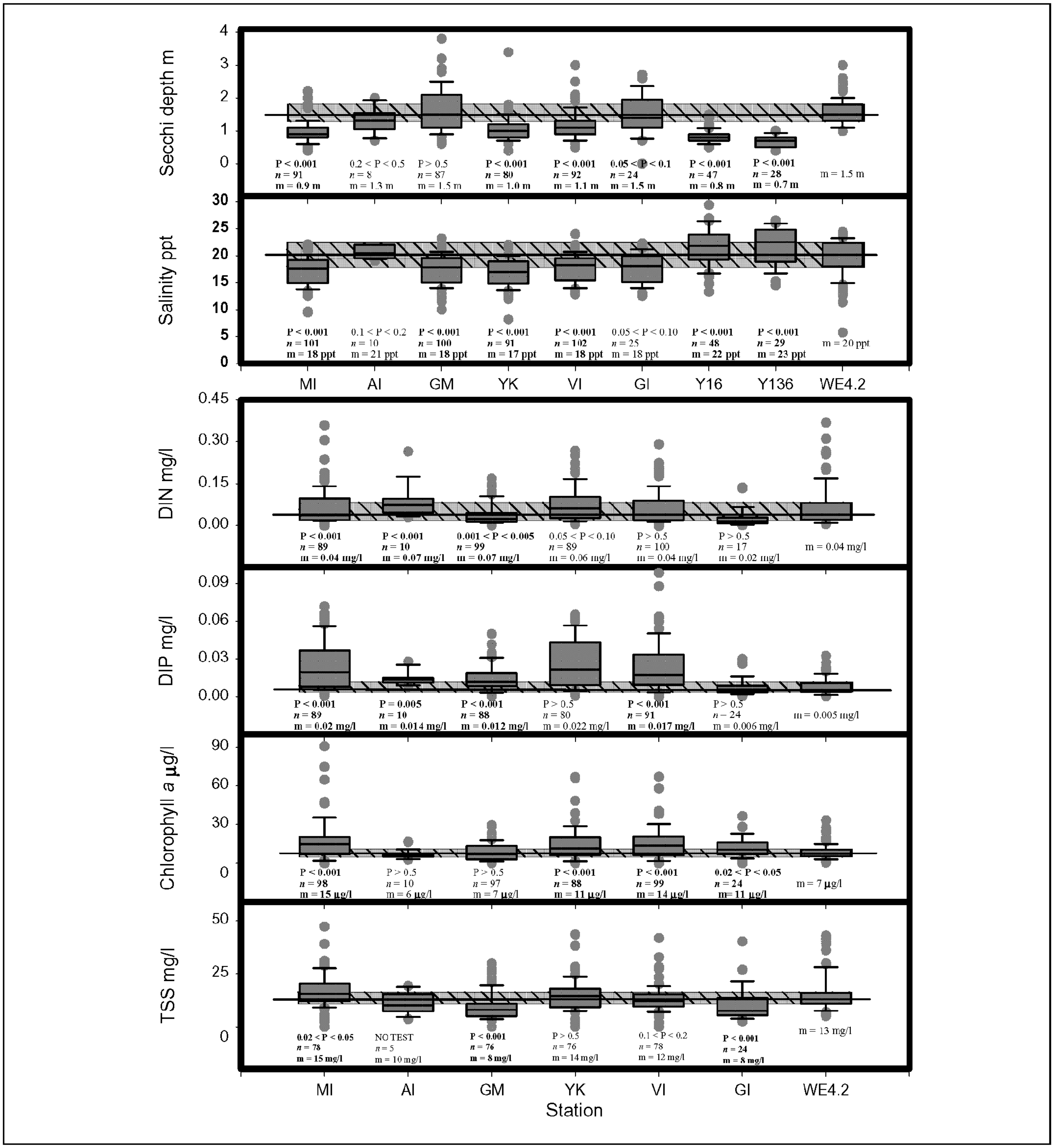

FIGURE IX-2. Representative box plot (from Lower York River). Circles above and below each plot are outliers. Grey band with diagonal black lines shows the interquartile range of the midchannel data. The solid line extending horizontally through all plots shows the median of the midchannel data. Under each plot are the results of the Wilcoxon rank-pair test, the *n* of the test and the median from each station's data. Stations MI, AI, GM, YK and GI are Virginia Institute of Marine Science stations, Y16 and Y136 are citizen monitoring stations managed by the Alliance for the Chesapeake Bay.

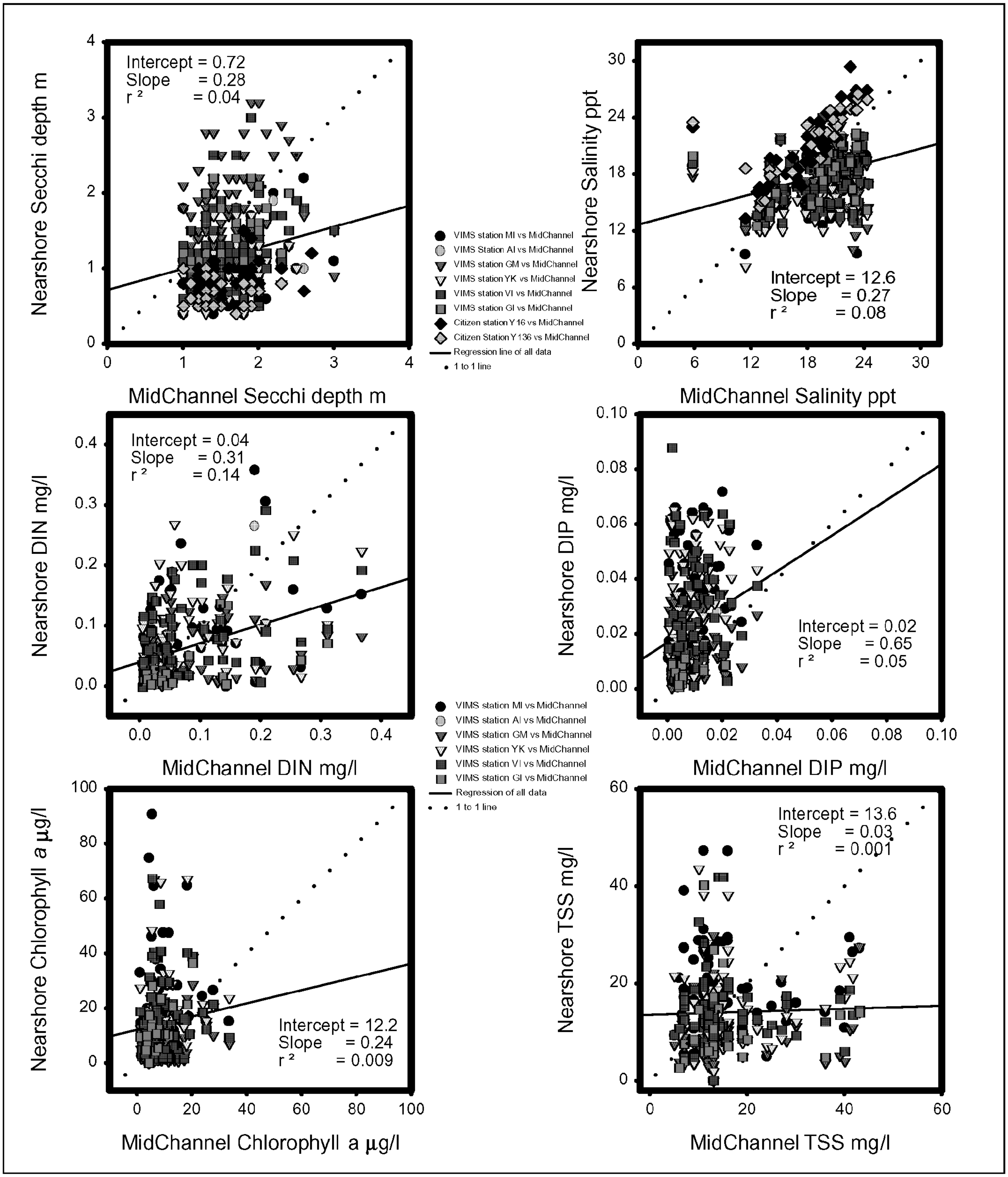

FIGURE IX-3. Representative Scatter Plot. Scatter plots showing the data from Figure IX-2. The Y axes are all the nearshore data versus the X axes which are data from the corresponding midchannel station.

TABLE IX-2. Percentage of total comparisons by area showing nearshore and midchannel conditions were similar by the Wilcoxon rank-pair test. The number in parentheses indicates the total number of comparisons performed in that tributary (not the number of stations). ND indicates that no data were available for the comparison. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids.

Tributary	Secchi Depth	Salinity	DIN	DIP	Chlorophyll *a*	TSS
Upper Bay	35% (20)	ND	42% (24)	ND	17% (24)	ND
Middle River	100% (1)	ND	ND	ND	ND	ND
Magothy River	54% (26)	54% (26)	56% (23)	85% (23)	92% (25)	92% (25)
Chester River	29% (14)	ND	ND	ND	ND	ND
Rhode River	0% [1]	0% (1)	ND	ND	0% (1)	ND
Choptank River	67% (12)	75% (12)	33% (12)	16% (12)	33% (12)	75% (8)
Patuxent River	50% (14)	27% (11)	66% (9)	66% (9)	ND	ND
Potomac River	44% (16)	ND	7% (14)	33% (12)	19% (16)	36% (14)
Rappahannock River	29% (7)	ND	ND	ND	ND	ND
Mobjack Bay	0% (1)	0% (1)	ND	ND	ND	ND
York River	19% (27)	16% (25)	20% (15)	33% (15)	20% (15)	7 % (50)
Poquoson River	0% (2)	0% (2)	ND	ND	ND	ND
James River	20% (15)	13% (8)	ND	ND	ND	ND

[1] Medians almost identical.

had similar values of the parameter of interest). The parameters are discussed individually, summarizing the results by mainstem Chesapeake Bay region and tidal tributary, using the following categories as descriptors based on the percentage of similar nearshore and midchannel comparisons: excellent (>75 percent), good (50–75 percent) and poor (<50 percent). Only results on a mainstem Chesapeake Bay region and tidal tributary-wide basis are discussed, however, the results at a specific midchannel station may differ from those of the mainstem Bay region or tributary as a whole. More specific results are expressed in the subsequent section.

Tributary Comparisons

Secchi Depth

Middle River showed excellent similarity (100 percent) between the midchannel station and the nearshore station, though it is important to note that there was only one nearshore station there. The Magothy, Choptank and Patuxent rivers showed good similarity between the midchannel and nearshore data (54, 67 and 50 percent similarity, respectively). However, the Upper Bay area, the Chester, Potomac, Rappahanock, York, Poquoson and James rivers, and Mobjack Bay showed poor similarity between the midchannel and nearshore conditions. For the Rhode River, there was only one comparison, which shows a significant difference between the nearshore and midchannel station, but the medians and interquartile ranges were almost identical, indicating that the stations were very similar, even though the statistics indicate a significant difference.

Salinity

The Magothy and Choptank rivers showed good similarity between the nearshore and midchannel stations (54 and 75 percent similarity, respectively), while the other comparisons that had salinity data—Rhode, Patuxent, York, Poquoson and James rivers and Mobjack Bay—have poor similarity (27 to 0 percent). The overall poor similarity between nearshore and midchannel salinities indicated that many of the nearshore stations had different water masses present than at the corresponding midchannel station. This may be because the nearshore stations were located slightly up or down the salinity gradient from the midchannel station.

Dissolved Inorganic Nitrogen

Of the comparisons that had dissolved inorganic nitrogen data, the Magothy and Patuxent rivers have good similarity between the nearshore and midchannel stations (56 and 66 percent, respectively), while the Upper Bay area, the Choptank, Potomac and York rivers have poor similarity (<33 percent). There were gradients in dissolved inorganic nitrogen-high values upstream and lower values downstream- in the Patuxent and Choptank rivers, which could explain some of the differences between nearshore and midchannel dissolved inorganic nitrogen data (Bergstrom, unpublished).

Dissolved Inorganic Phosphorus

Dissolved inorganic phosphorus showed a similar pattern as dissolved inorganic nitrogen. The Magothy River had excellent similarity between the nearshore stations and the midchannel station (85 percent) and the Patuxent River had good similarity between the nearshore and midchannel stations (66 percent), while the Upper Bay area, the Choptank, Potomac and York rivers showed poor similarity (< 33 percent). Again, longitudinal gradients could explain these differences.

Chlorophyll a

The Magothy River had excellent similarity between the nearshore and midchannel stations (92 percent). The Upper Bay area, the Choptank, Potomac and York rivers had poor similarity between the nearshore and midchannel environments (17, 33, 19 and 20 percent, respectively).

Total Suspended Solids

Again, the Magothy River had excellent similarity between the nearshore and midchannel data (92 percent) as did the Choptank River (75 percent). The Potomac and York rivers had poor similarity between the nearshore and midchannel stations (36 and 7 percent, respectively).

Overall Comparisons

The Magothy River midchannel station (MWT6.1) seems adequately to describe most nearshore areas in that river for all five SAV habitat parameters. However, this is a very short river, with tightly grouped stations. The midchannel stations in the Choptank seem adequately to describe the light penetration and total suspended solids conditions in the nearshore environment. The Patuxent River midchannel stations seem adequately to describe the light and nutrient conditions in the nearshore areas. In the Middle River, the state water-quality monitoring light penetration data can be applied to the adjacent nearshore areas. The Upper Bay area, the Chester, Potomac, Rappahanock, York, Poquoson and James Rivers, and Mobjack Bay have more significant differences between the nearshore and midchannel stations than the other areas mentioned. The section below takes a more site-specific look into these results, by determining distances from an individual midchannel station that characterize the nearshore environment.

Spatial Similarities

One of the objectives of this study was to determine the distance from midchannel stations over which water quality data can be used to assess nearshore conditions. The distances upstream and downstream were estimated using the furthest distance from a midchannel station that yielded a nonsignificant result between the nearshore and midchannel stations for each parameter (Table IX-3).

TABLE IX-3. Estimated distances from midchannel monitoring stations to the farthest point where the nearshore/midchannel data are comparable. Actual distances may be greater as listed distances based on existing nearshore stations. < indicates a statistically significant difference between the midchannel station and the closest nearshore station, therefore the distance is less than what is presented. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids.

Station	Secchi Depth	Salinity	DIN	DIP	TSS	Chlorophyll *a*
Upper Bay						
MCB1.1	3.0 km	ND	3.0 km	ND	ND	3.0 km
MCB2.1	8.0 km upstream	ND	<2.5 km	ND	ND	8.0 km upstream
MCB2.2	6.0 km upstream	ND	low n	ND	ND	low n
MET1.1	<4.4 km downstream	ND	<4.4 km downstream	ND	ND	<4.4 km downstream
MET2.3	2.0 km	ND	< 2.0 km	ND	ND	2.0 km
MET3.1	< 4.7 km upstream < 0.2 km downstream	ND	< 4.7 km upstream < 0.2 km downstream	ND	ND	< 4.7 km upstream < 0.2 km downstream
Middle River						
MWT3.1	1.4km	ND	ND	ND	ND	ND

continued

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TABLE IX-3. Estimated distances from midchannel monitoring stations to the farthest point where the nearshore/midchannel data are comparable. Actual distances may be greater as listed distances based on existing nearshore stations. < indicates a statistically significant difference between the midchannel station and the closest nearshore station, therefore the distance is less than what is presented. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids (*continued*).

Station	Secchi Depth	Salinity	DIN	DIP	TSS	Chlorophyll *a*
			Magothy River			
MWT6.1	2.5 km upstream 7.8 km downstream (not MR10 or 11)	<0.2 km However = MR13 (7.8 km downstream)	1.5 km upstream 5.4 km downstream not MR9	1.5 km upstream 7.8 km downstream	2.5 km upstream 6.5 km downstream not MR7, 11	2.5 km upstream 7.8 km downstream not MR5
MR6 (internal MC)	2.5 km upstream , but not MR5 (across stream) <0.9 km downstream	2.5 km upstream 7.8 km downstream	1.5 km upstream 5.3 km downstream	2.0 km upstream 7.8 km downstream not MR10	2.5 km upstream 6.5 km downstream not MR7, 10	2.5 km upstream 7.8 km downstream not MR11
			Rhode River			
MWT8.2	0.9 km (sig, medians almost =)	0.9 km	ND	ND	ND	< 0.9 km
			Choptank River			
MET5.1	10 km upstream < 5.5 km downstream	< 10 km upstream 5.5 km downstream	10 km upstream but 2.3 km upstream is sig 5.5 km downstream	2.3 km upstream < 5.5 km downstream	10 km upstream 5.5 km downstream	< 2.3 km upstream < 5.5 km downstream
MET5.2	3.5 km upstream [1] 8.6 km downstream	2.3 km upstream 5.5 km downstream	<2.3 km upstream < 5.5 km downstream	8.6 km upstream to 2.3 km upstream < 5.5 km downstream	8.6 km upstream to 2.3 km upstream 7.4 km to 8.2 downstream	2.3 km upstream 5.5 km downstream
MEE2.1 No downstream	7.3 km upstream 7.2 km N	7.3 km all directions	7.3 km upstream < 6.1 km N 4.7 km S	< 4.7 km	7.3 km all directions	< 7.3 km upstream 7.2 km N <4.7 km S

Modified using Parham, 1996

continued

Patuxent River

Station	Secchi Depth	Salinity	DIN	DIP	TSS	Chlorophyll *a*
PXT0494	ND	ND	2.5 km downstream	2.5 km downstream	ND	ND
WXT0001	< 0.8 km upstream	ND	0.8 km upstream	0.8 km upstream	ND	ND
PXT0456	< 0.8 km upstream	ND	0.8 km upstream	0.8 km upstream	ND	ND
XED4892	2.6 km upstream < 0.85 km downstream	2.6 km upstream < 0.85 km downstream	2.6 km upstream 0.85 km downstream	2.6 km upstream <0.85 km downstream	ND	ND
XDE9401	5 km upstream [1] <2.2 km downstream	< 2.2 km upstream or downstream	3.7 km downstream (only 1 station)	3.7 km downstream (only 1 station)	ND	ND
XDE5339	2 km upstream [1]	ND	1.4 km (only 1 station)	1.4 km (only 1 station)	ND	ND
XDE2792	5 km upstream [1] 4.2 km upstream St. Leonard's creek 3.1 km across 1.8 km downstream	< 1.75	< 4.2 km upstream St. Leonard's creek, only 1 station	4.2 km upstream St. Leonard's creek, only 1 station	ND	ND

Potomac River

XFB1433 (1 station)	< 1.9 km	Tidal fresh	<1.9km	< 1.9 km	< 1.9 km	< 1.9 km
XFB2470	< 3.4 km	Tidal fresh	< 3.4 km	< 3.4 km	< 3.4 km	< 3.4 km

[1] Modified using Parham, 1996

continued

TABLE IX-3. Estimated distances from midchannel monitoring stations to the farthest point where the nearshore/midchannel data are comparable. Actual distances may be greater as listed distances based on existing nearshore stations. < indicates a statistically significant difference between the midchannel station and the closest nearshore station, therefore the distance is less than what is presented. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids (*continued*).

Station	Secchi Depth	Salinity	DIN	DIP	TSS	Chlorophyll *a*
				Rappahanock River		
TF3.1 A (1 station)	6.2 km upstream	ND	ND	ND	ND	ND
TF3.2 (1 station)	0.8 km	ND	ND	ND	ND	ND
LE3.2	< 3.3 km	ND	ND	ND	ND	ND
				Magothy River		
WE4.1	< 5.5 km	< 5.5 km	ND	ND	ND	ND
				York River		
RET 4.1 (1 station)	< 9.1 km	9.1 km	ND	ND	ND	ND
RET 4.3 (1 station)	< 2.5 km	< 2.5 km	ND	ND	ND	ND
LE4.1	< 2.1 km	2.1 km across 3.1 km upstream	ND	ND	ND	ND
LE4.2	< 2.0 km upstream 5.3 km downstream	< 2.0 km	< 2.8 km upstream < 5.3 km downstream	2.8 km upstream 5.3 km downstream	7.8 km upstream 5.3 km downstream	< 2.8 km upstream < 5.3 km downstream
LE4.3	< 1.8 km upstream < 5.6 km downstream	<1.8 km	< 1.8 km	< 1.8 km upstream 5.6 km downstream	< 1.8 km upstream 5.6 km downstream	< 1.8 km upstream 5.6 km downstream

continued

York River (cont'd.)

Station	Secchi Depth	Salinity	DIN	DIP	TSS	Chlorophyll *a*
WE4.2	3.7 km upstream 1.2 km North 2.3 km South No data downstream	3.7 km upstream < 1.2 km N 2.3 km S No data downstream	11.3 km upstream < 1.2 km N 2.3 km S No data downstream	< 3.7 km upstream < 1.2 km N 2.3 km S No data downstream	Conflicting results upstream < 1.2 km across channel	3.7 km upstream 1.2 km N < 2.3 km S No data downstream
Poquoson Rover						
WE4.3	< 4.9 km	< 4.9 km	ND	ND	ND	ND
James River						
TF5.3	No data upstream 2.7 km downstream	Tidal fresh	ND	ND	ND	ND
TF5.4 (1 station)	<4.3 km	Tidal fresh	ND	ND	ND	ND
TF5.5	No data upstream <0.3 km across < 5.8 km downstream	Tidal fresh	ND	ND	ND	ND
TF5.5A	3.0 km upstream No data downstream	Tidal fresh	ND	ND	ND	ND
RET5.2 (1 station)	No data upstream < 8.9 km downstream	No data upstream < 8.9 km downstream	ND	ND	ND	ND

continued

TABLE IX-3. Estimated distances from midchannel monitoring stations to the farthest point where the nearshore/midchannel data are comparable. Actual distances may be greater as listed distances based on existing nearshore stations. < indicates a statistically significant difference between the midchannel station and the closest nearshore station, therefore the distance is less than what is presented. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids (*continued*).

James River (cont'd.)

Station	Secchi	Salinity	DIN	DIP	TSS	Chlorophyll *a*
LE5.1 (1 station)	3.1 km upstream No data downstream	< 3.1 km upstream No data downstream	ND	ND	ND	ND
LE5.2 (1 station)	< 14.5 km upstream < 9.4 km downstream	< 14.5 km upstream < 9.4 km downstream	ND	ND	ND	ND
LE5.3	<13.8 km upstream <9.2 km downstream	<13.8 km upstream <9.2 km downstream	ND	ND	ND	ND
LE5.4 (1 station)	< 7.3 km upstream no data downstream	7.3 km upstream no data downstream	ND	ND	ND	ND

If there was only one nearshore station compared to a midchannel station, the distance is expressed as a radius. For multiple nearshore stations per comparison, the distances upstream and downstream of the midchannel station are noted. Where possible, cross-stream distances are expressed as the cardinal directions (North = N, South = S, etc.). Figures IX-4a-o are maps showing these distances in relation to the midchannel station.

For each parameter, estimates were made of the distance from midchannel stations that nearshore conditions could be characterized using midchannel data. Using the values given in Table IX-3, the 10th and 25th percentile and the median distances were determined for each parameter. The assumption was that, without nearshore data available, the percentile (or median) distance for each parameter will describe how far from a midchannel station its water quality data can characterize the nearshore environment. The level of risk in using the midchannel data to characterize the nearshore area is equal to the percentile. For example, if the 10th percentile distance is 1 kilometer, there is a 10 percent chance that data from a midchannel station will not adequately describe the nearshore environment one kilometer away. Conversely, there is 90 percent chance that the midchannel data will describe the nearshore condition to at least one kilometer distance from the midchannel station. These distances, by each parameter tested, are listed in Table IX-4.

Attainment of Habitat Requirements

Another analysis was performed to examine the relationship of nearshore and midchannel water quality data to the SAV habitat requirements. This was done because even though nearshore and midchannel data may not be statistically similar, they both may yield the same conclusion relative to the SAV habitat requirements. Nearshore and midchannel paired data were compared individually to the 1992 SAV habitat requirements for 1-meter restoration (Batiuk *et al.* 1992) to include as many tidal tributaries as possible, since each component (light penetration, dissolved nutrients, chlorophyll *a* and total suspended solids) could be considered separately. Many of the nearshore stations used in this study do not have a complete suite of parameters, and the new minimum light requirements described in this report require light penetration, dissolved nutrients and total suspended solids to deliver an integrated answer to whether or not they meet the minimum habitat requirement. Therefore, the new minimum light requirement was inappropriate to use for this analysis. The nearshore and midchannel results were then compared to see if they agreed (i.e., both either met or failed to meet the habitat requirement) or disagreed, i.e., one met and one failed. (Table IX-5).

Secchi Depth

For most areas of the Bay, the agreement between the nearshore and midchannel stations was good to excellent (50 percent agreement), with the exception of the Rappahanock and Poquoson rivers and Mobjack Bay (41, 24, and 13 percent, respectively). With these exceptions, it is possible to consider that the nearshore environments will reflect the results of applying the habitat requirements to the midchannel data.

Dissolved Inorganic Nutrients

In terms of the limited number of tidal tributaries that have nearshore nutrient data, most have fairly good agreement between nearshore and midchannel attainment of the SAV nutrient habitat requirements (> 55 percent). The Patuxent River is the exception, with less than 32 percent agreement. With this exception, SAV habitat requirement analysis of the dissolved inorganic nutrient conditions in the midchannel are applicable to the nearshore environment.

Chlorophyll a

In terms of the areas for which nearshore chlorophyll *a* data are available, the agreement is fairly good between the nearshore and midchannel comparison to the habitat requirement (> 64 percent). The exceptions are the Upper Bay area and the York River (47 and 44 percent, respectively).

Total Suspended Solids

Of the four areas that have total suspended solids data—the Magothy, Choptank, Potomac and York rivers—the Choptank River (68 percent) and the Potomac River (75 percent) had good agreement, while the Magothy (31 percent) and the York (40 percent) rivers had poor agreement. Therefore, it is appropriate to use the midchannel data to determine if an area meets the SAV habitat requirements for total suspended solids for the Choptank and Potomac

TABLE IX-4. Percentile distances from midchannel water quality monitoring stations from which it is possible to characterize the nearshore environment.

Parameter	Percentile distance (kilometers)		
	10th	25th	Median
Secchi Depth	1.0	2.1	3.9
Salinity	1.6	2.2	4.1
Dissolved Inorganic Nitrogen	1.1	1.8	3.0
Dissolved Inorganic Phosphorous	1.2	2.1	3.4
Chlorophyll *a*	2.4	3.6	4.0
Total Suspended Solids	1.7	2.7	5.5

TABLE IX-5. Comparison of the 1992 SAV habitat requirements attainment between nearshore and midchannel water quality monitoring data. Percent shown is the number of times both the nearshore and midchannel stations meet or fail the respective habitat requirement. The number in parentheses is the total number of paired observations. DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus; and TSS = total suspended solids.

Area	Secchi Depth	DIN	DIP	Chlorophyll *a*	TSS
Upper Bay	63% (294)	87% (182)	ND	47% (258)	ND
Middle River	98% (42)	ND	ND	ND	ND
Magothy River	69% (835)	62% (583)	65% (658)	64% (571)	31% (444)
Chester River	72% (251)	ND	ND	ND	ND
Rhode River	70% (47)	ND	ND	77% (47)	ND
Choptank River	76% (369)	77% (316)	70% (357)	75% (365)	68% (317)
Patuxent River	75% (970)	31% (610)	32% (584)	ND	ND
Potomac River	96% (1,400)	64% (949)	81% (1,402)	90% (1,438)	75% (1,130)
Rappahanock River	41% (140)	ND	ND	ND	ND
Mobjack Bay	13% (16)	ND	ND	ND	ND
York River	60% (1,398)	63% (1,294)	55% (1,303)	44% (1,323)	40% (1,159)
Poquoson River	24% (79)	ND	ND	ND	ND
James River	78% (651)	ND	ND	ND	ND
All tributaries	74% (6,492)	61% (3,934)	63% (4,304)	67% (4,002)	54% (3,050)

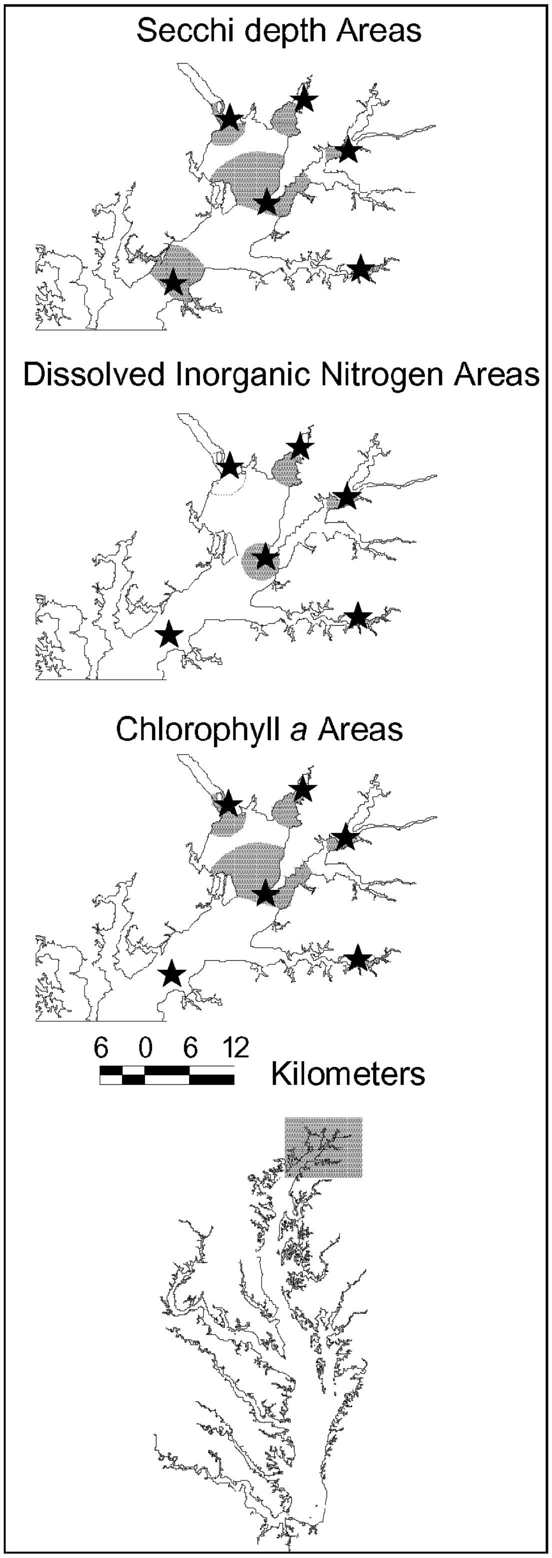

FIGURE IX-4a. **Maps of Upper Bay Region,** showing approximate distance from a mid-channel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth, dissolved inorganic nitrogen and chlorophyll *a* data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

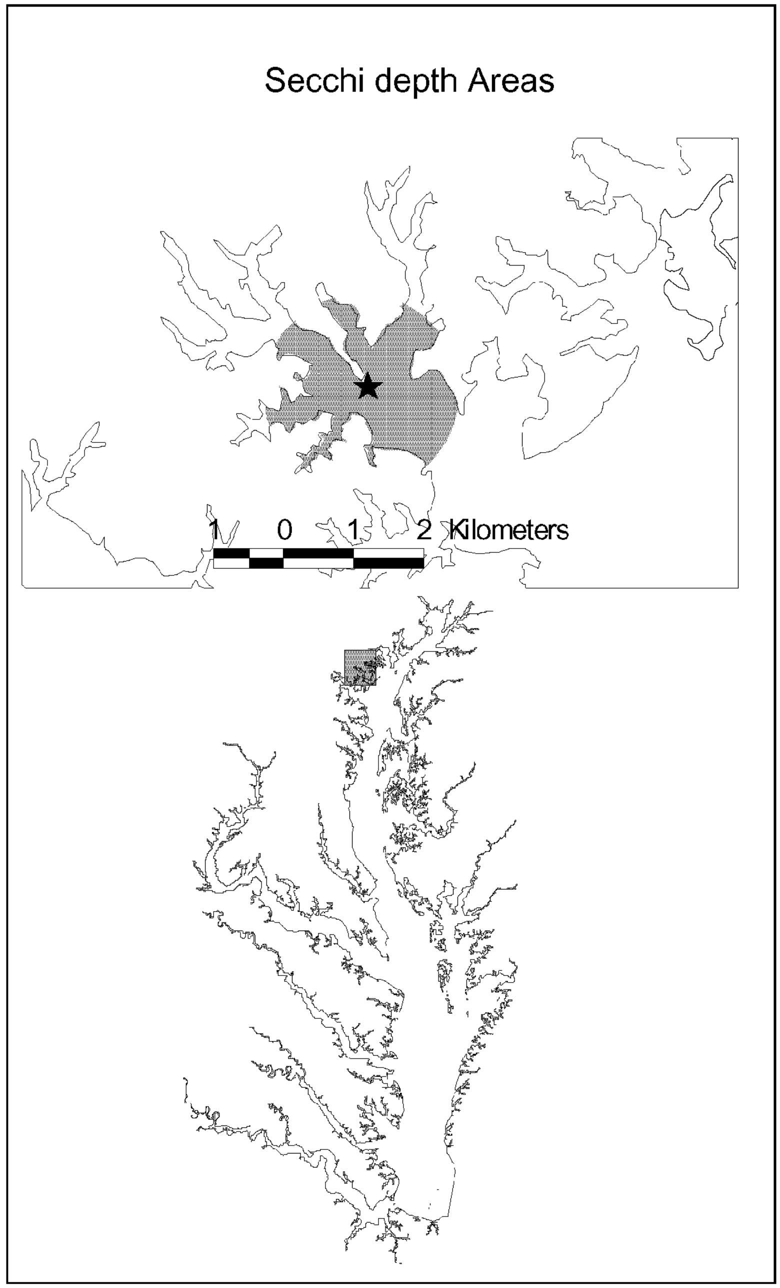

FIGURE IX-4b. **Map of Middle River,** showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

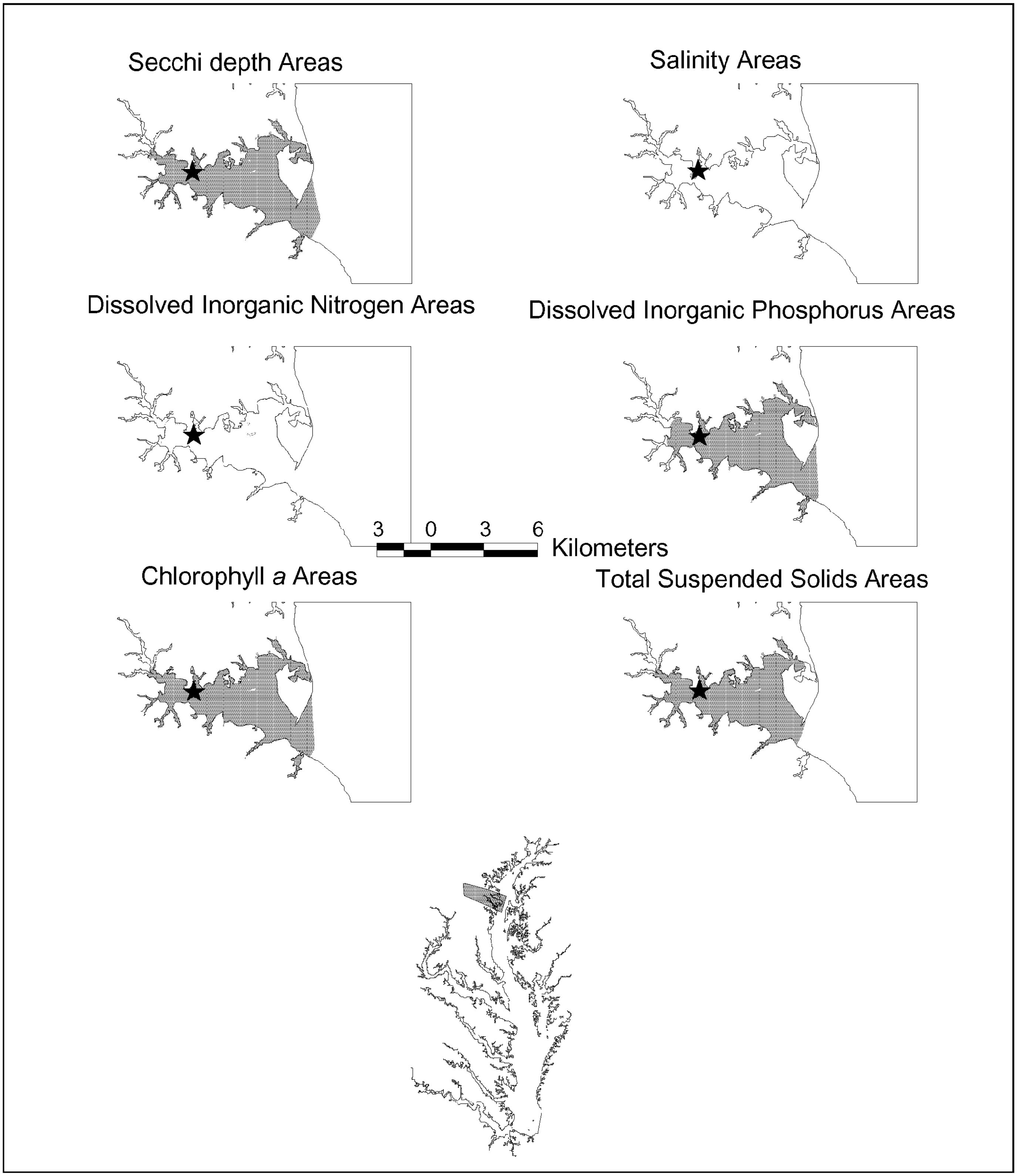

FIGURE IX-4c. Maps of Magothy River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. All parameters of interest had data available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

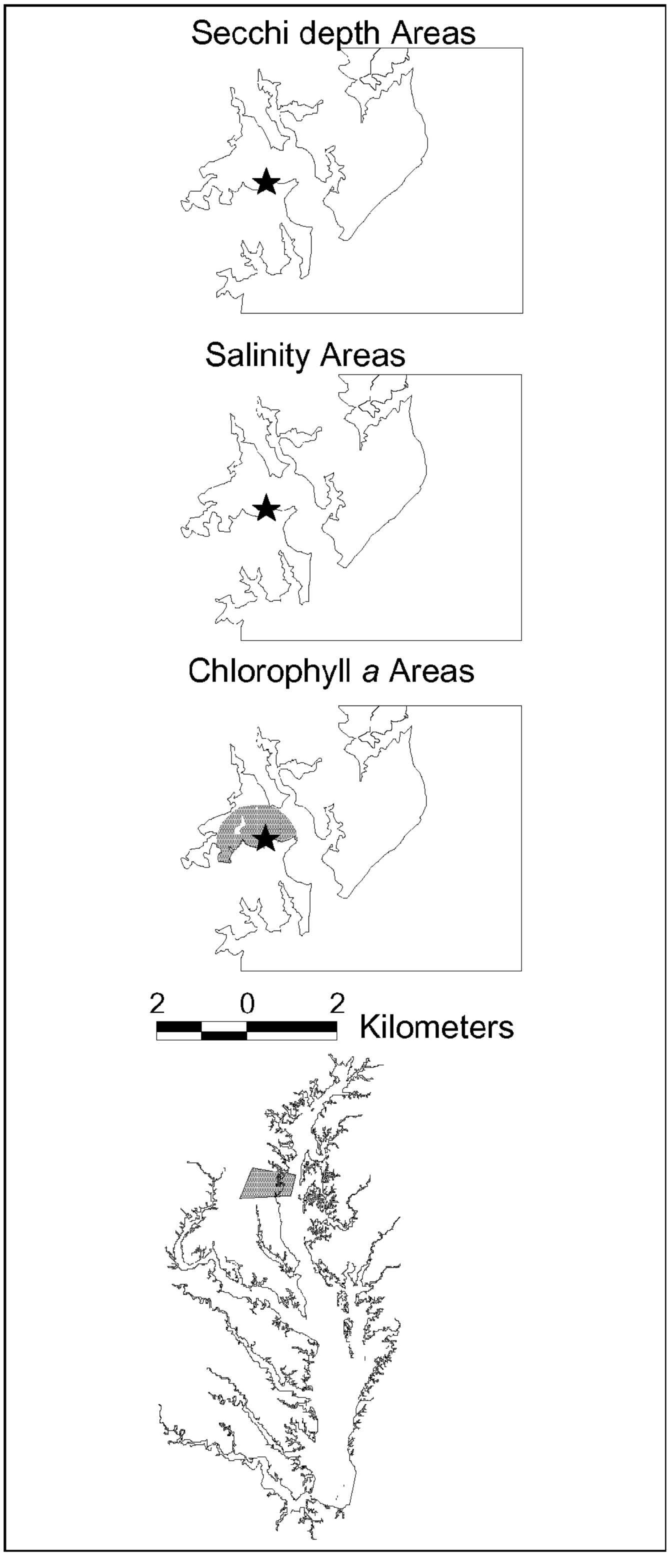

FIGURE IX-4d. Maps of Rhode River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Secchi depth, salinity, and chlorophyll *a* data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

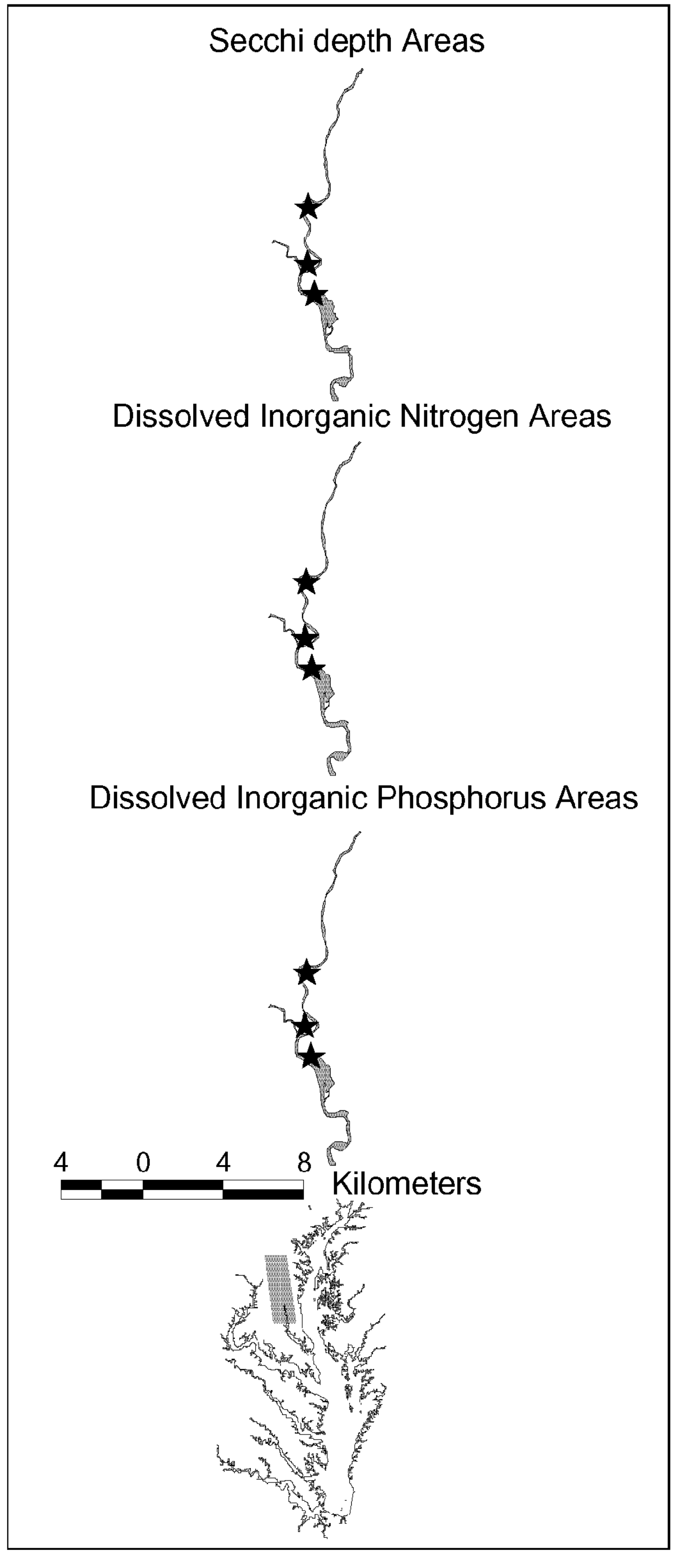

FIGURE IX-4e. Maps of Upper Patuxent River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth, dissolved inorganic nitrogen, an dissolved inorganic phosphorus data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

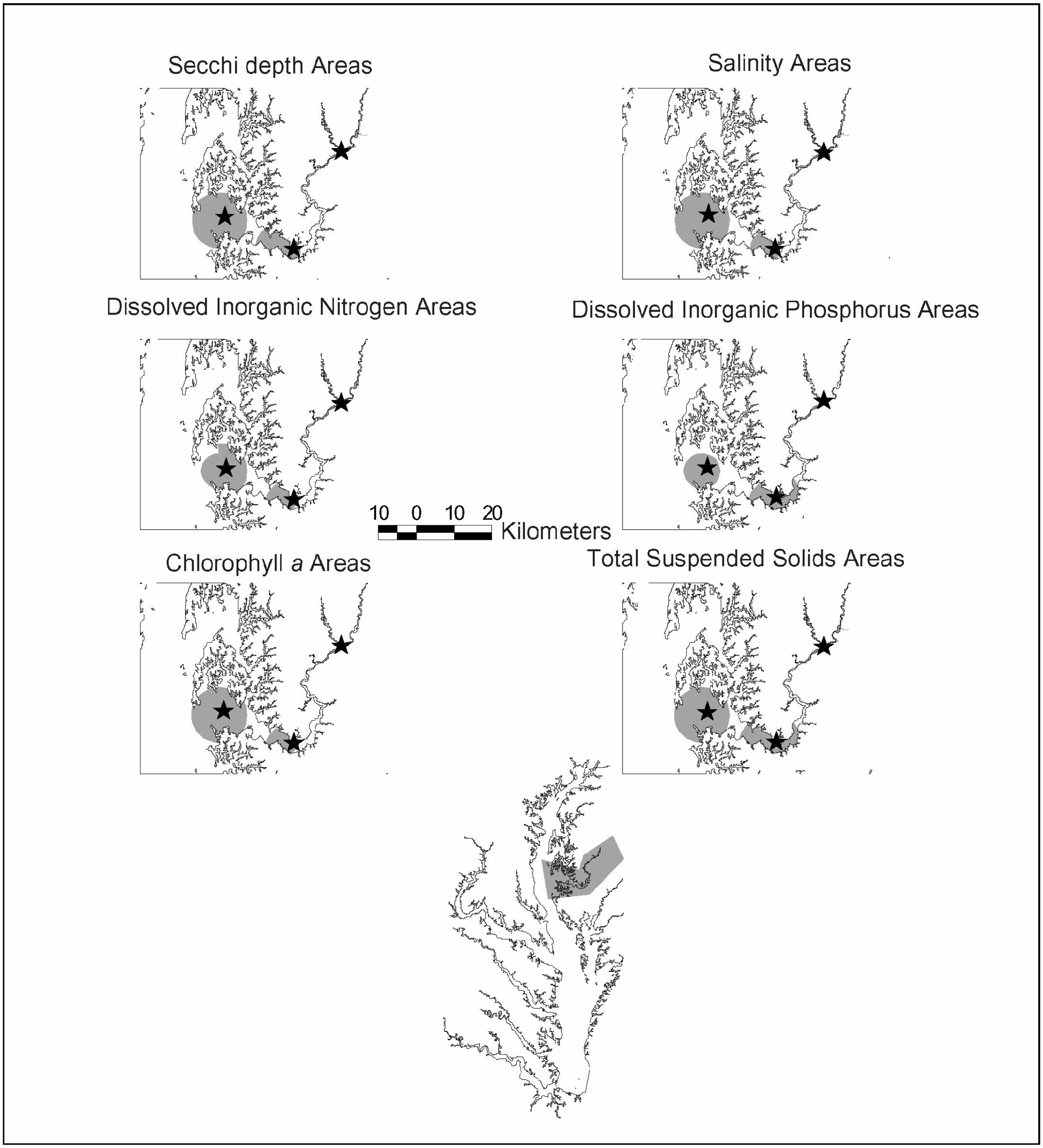

FIGURE IX-4f. Maps of Choptank River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. All parameters of interest had data available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

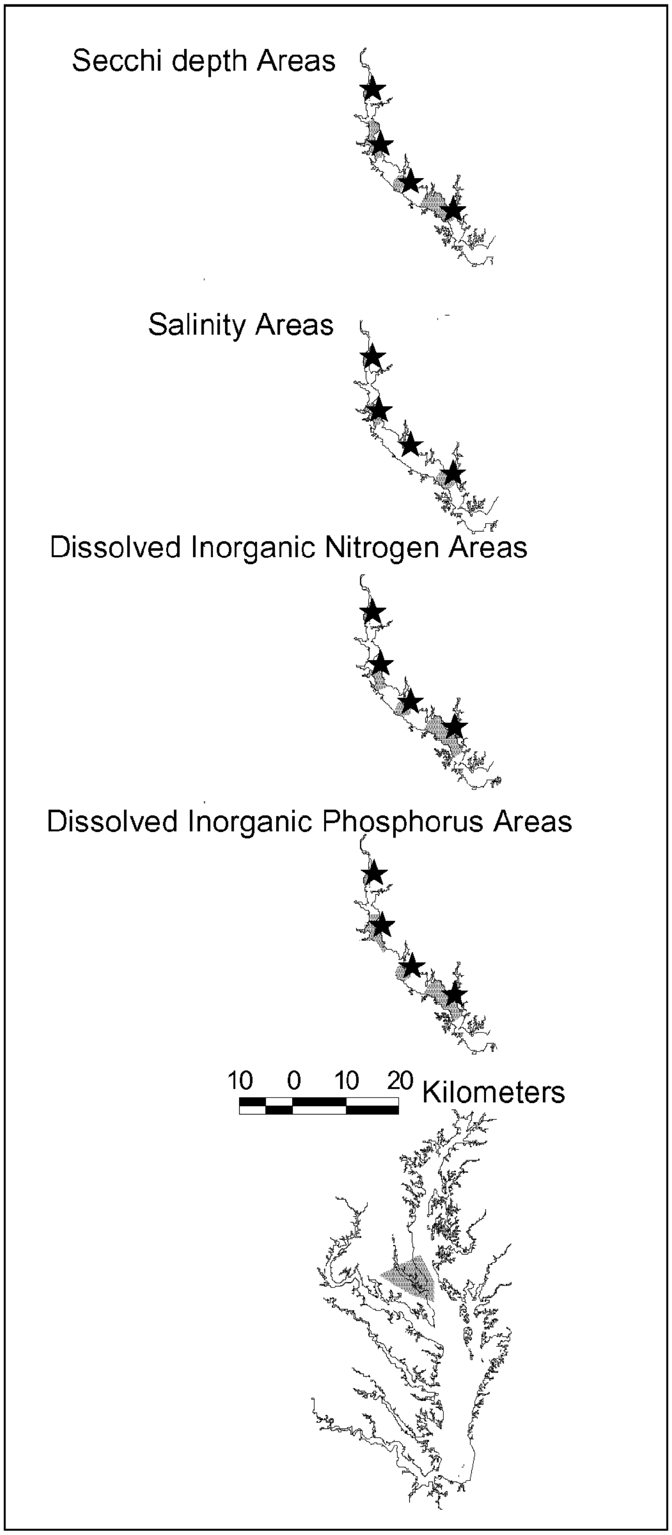

FIGURE IX-4g. Maps of Lower Patuxent River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Secchi depth, salinity, dissolved inorganic nitrogen, and dissolved inorganic phosphorus data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

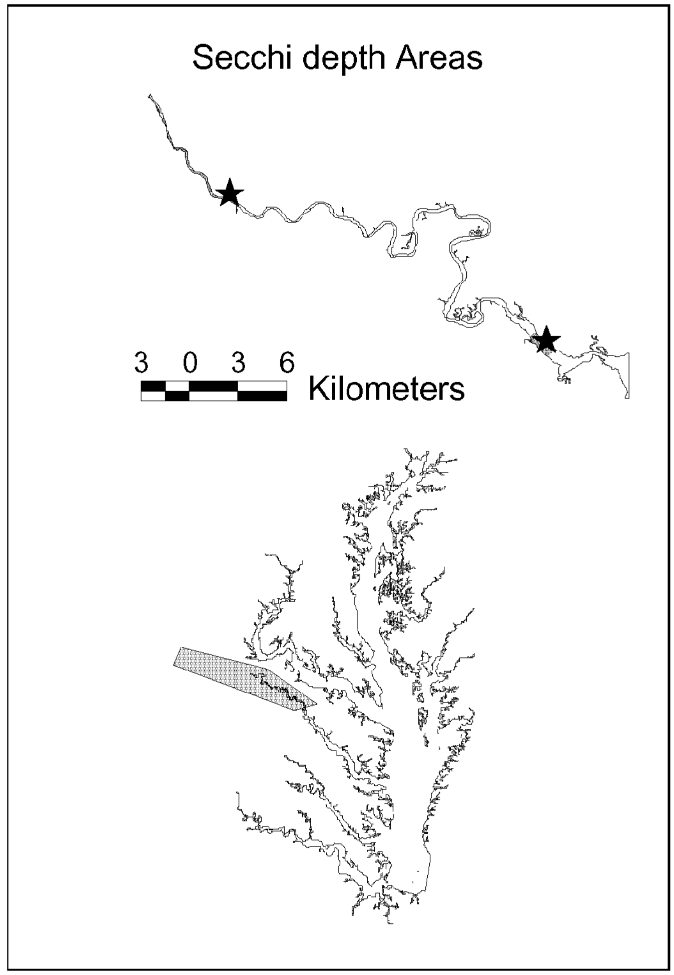

FIGURE IX-4h. Maps of Upper Rappahannock River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

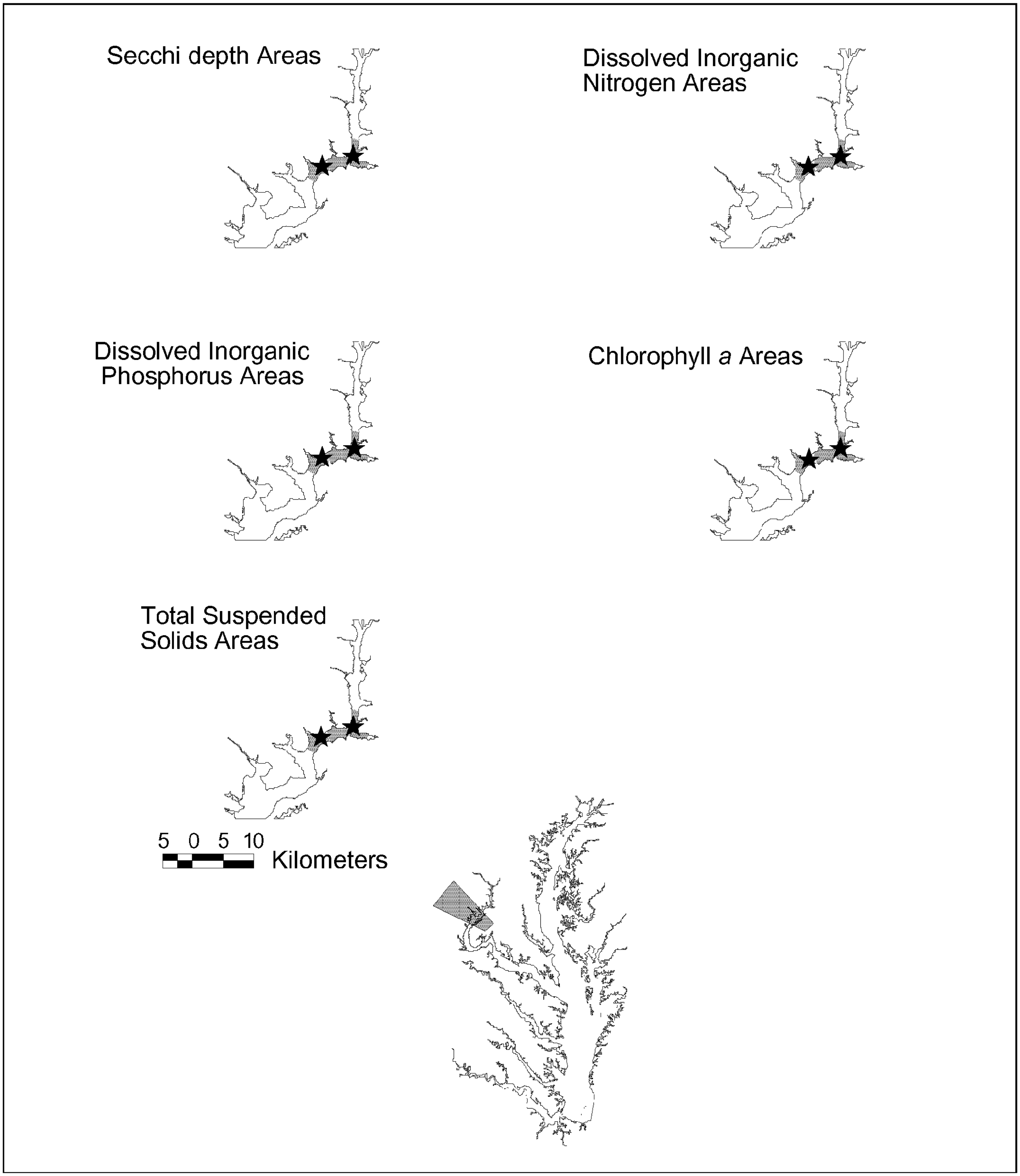

FIGURE IX-4i. Maps of Upper Potomac, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. All parameters had data available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

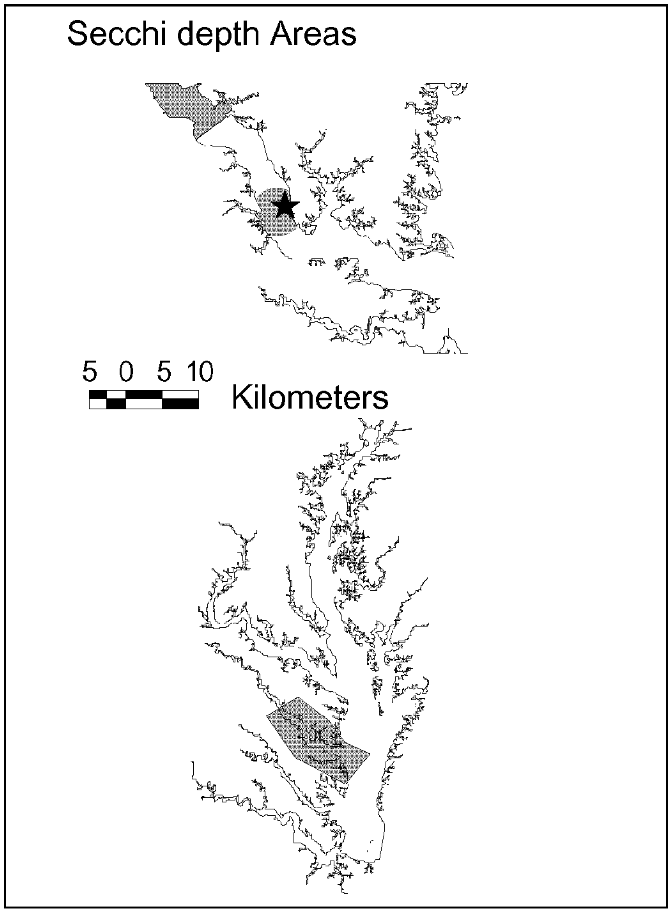

FIGURE IX-4j. **Maps of Lower Rappahannock River,** showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

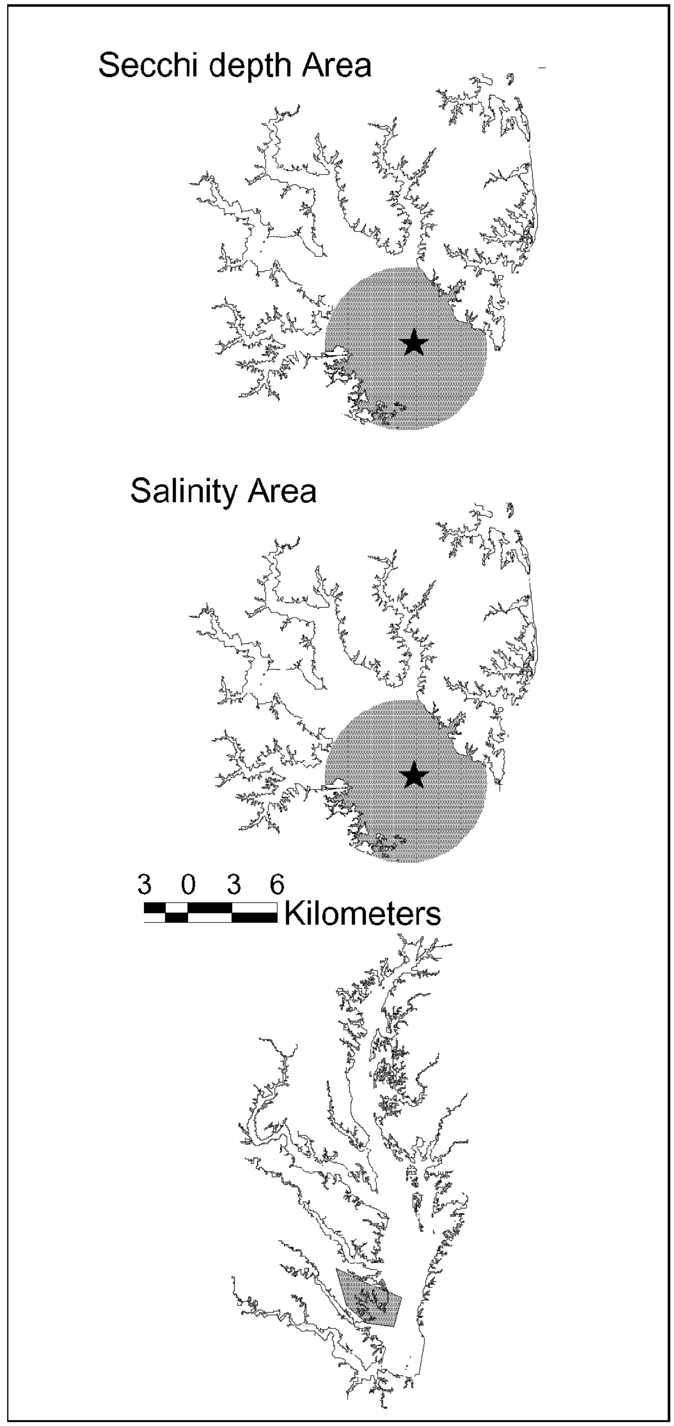

FIGURE IX-4k. **Maps of Mobjack Bay**, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth and salinty data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

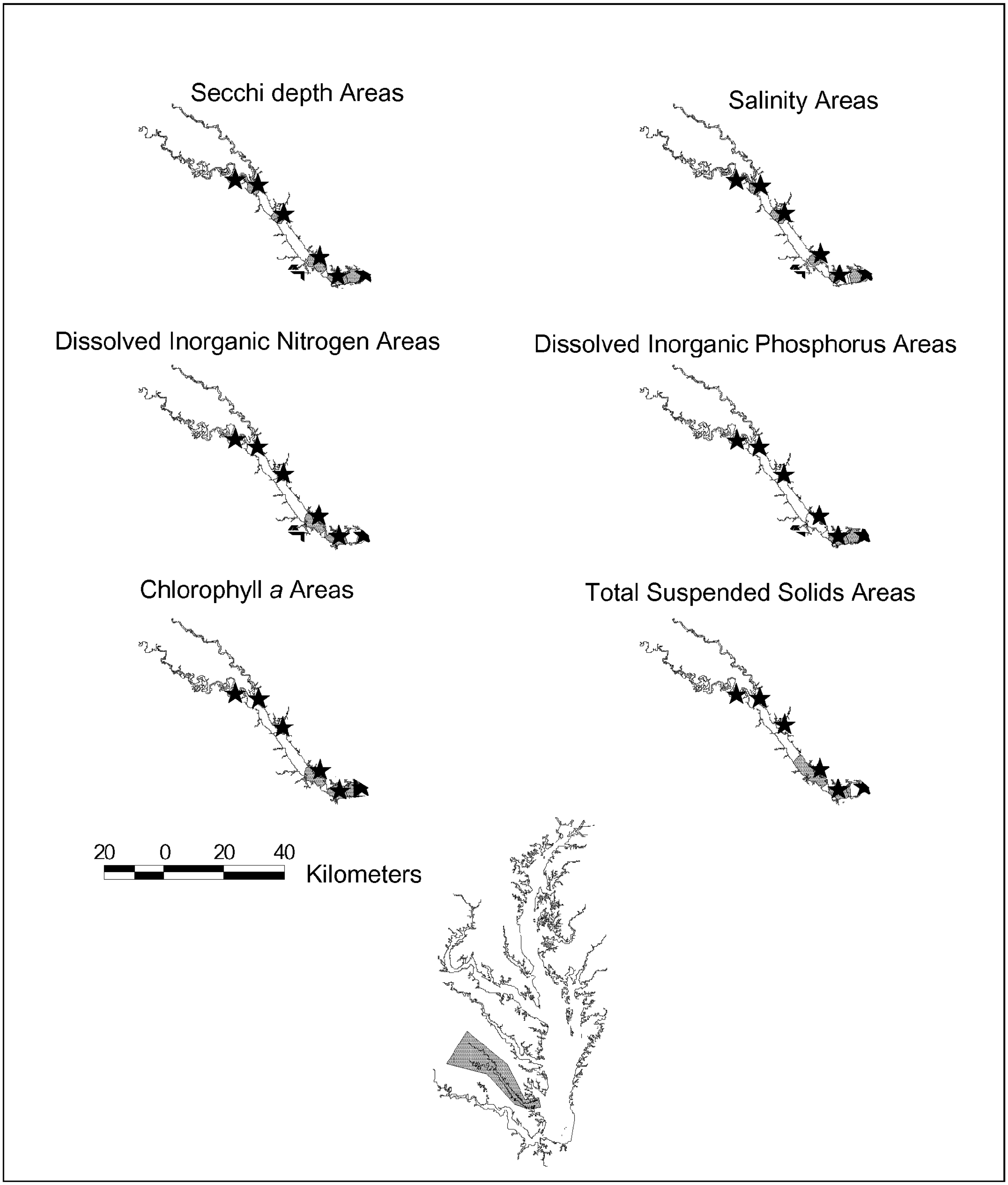

FIGURE IX-4l. Maps of York River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. All parameters had data available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

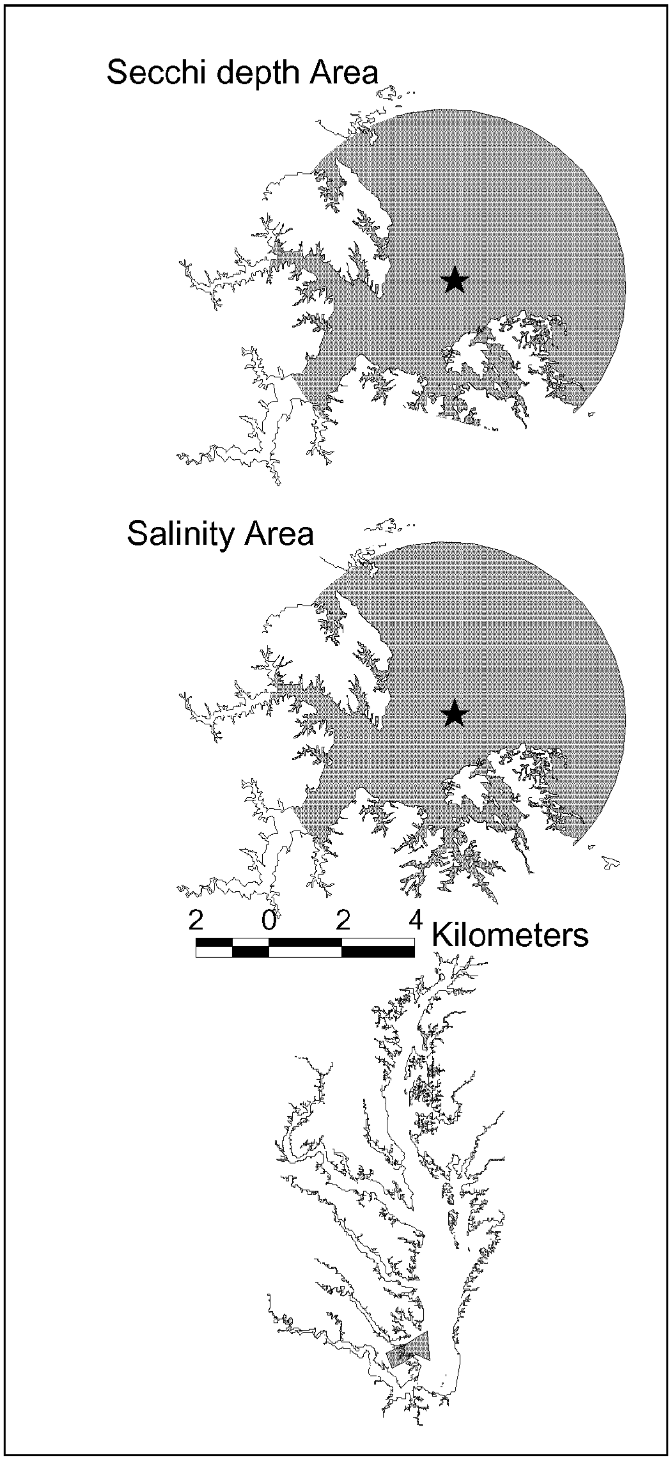

FIGURE IX-4m. Maps of Poquoson River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth and salinity data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

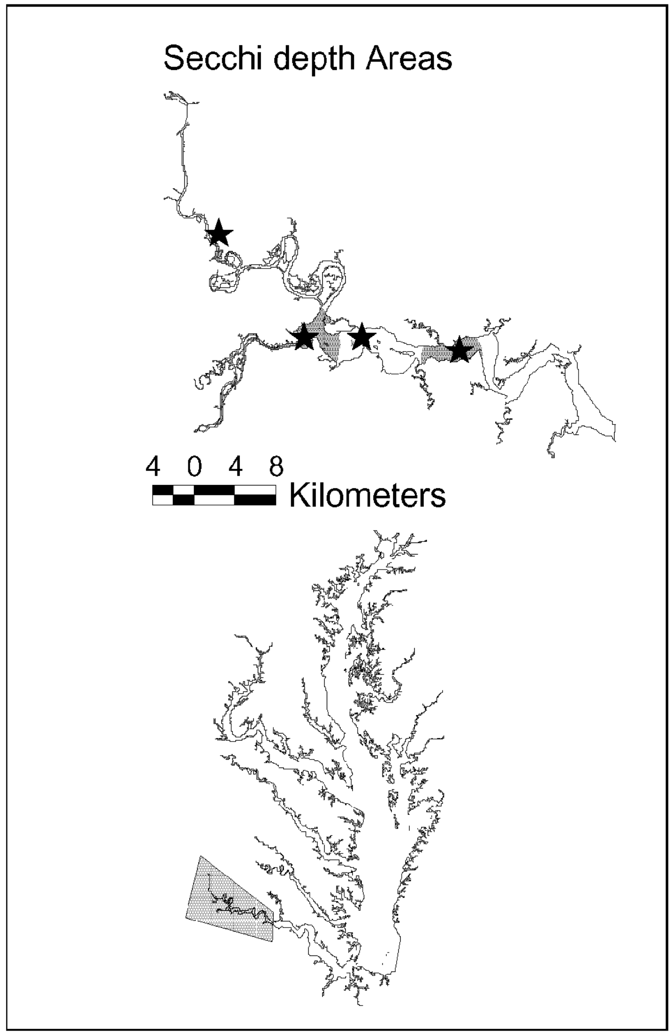

FIGURE IX-4n. Map of Upper James River, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

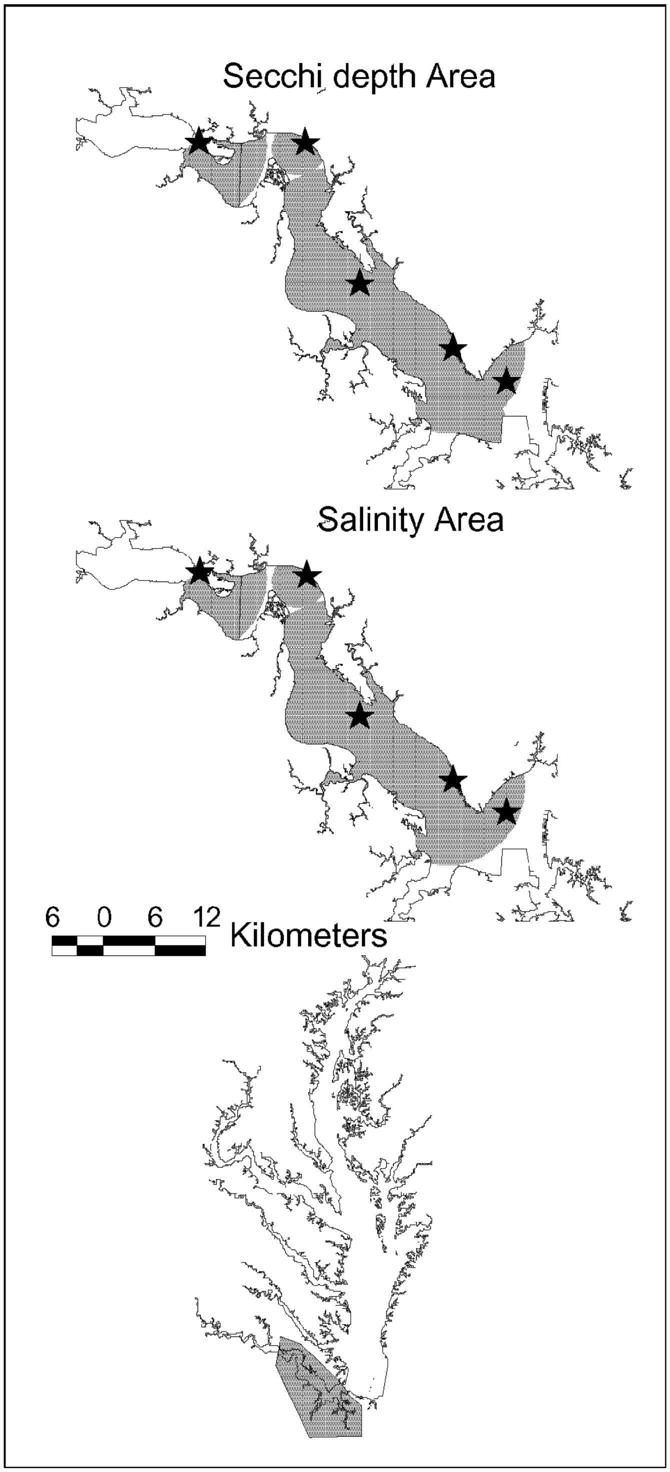

FIGURE IX-4o. **Map of Lower James River**, showing approximate distance from a midchannel water quality monitoring station (shown as a ✶), where it is possible to use midchannel water quality data to characterize the nearshore environment. Only Secchi depth and salinty data were available for comparison in this region of Chesapeake Bay. Shaded area in the baywide map shows area of enlargement.

FINDINGS

The summarized results of the paired station statistical analysis comparisons (Table IX-2) frequently exhibit a different pattern than the attainment data (Table IX-5). For Secchi depth, the Upper Bay area, the Chester, Rhode, Choptank, Potomac, York and James rivers show poor statistical similarity (< 50 percent of the statistical analyses had a nonsignificant result), while the SAV habitat requirement attainment agreement for these same areas is much higher (> 60 percent). For the nutrient data, the Upper Bay area, and the Rhode, Choptank, Potomac and York rivers show similar discrepancies, with statistical analyses showing low similarity (< 50 percent), while SAV habitat requirement attainment analyses show much higher agreement (> 50 percent). For the Patuxent River, this is reversed. The statistics show a fairly high degree of similarity (66 percent), but a low degree of SAV habitat requirement attainment agreement (< 32 percent). Chlorophyll *a* also has a discrepancy between the statistical and attainment analyses for the Upper Bay area and the Rhode, Choptank, Potomac and York rivers. The Magothy, Potomac and York rivers exhibit different conclusions from the statistical and attainment analyses for total suspended solids. The reason for these discrepancies is that although the two stations being compared may not be statistically similar, if both have a majority of their values for the parameter of interest firmly on the "met" or "failed" side of the habitat requirement, then the attainment results will be consistent.

CONCLUSIONS

There are wide variations in the results of the statistical comparisons between nearshore and midchannel data within the tidal tributaries and mainstem Chesapeake Bay. Decisions to use midchannel data to characterize nearshore conditions should be done on a site-by-site basis.

It is possible to determine a distance from a specific midchannel station for which it is appropriate to use the midchannel distance to characterize the nearshore environment. Measurements between nearshore and midchannel stations were comparable 90 percent of the time, between 1 and 2 kilometers from the midchannel station, though this radius differs on a site-by-site basis.

With the exceptions noted above, the midchannel and nearshore areas usually provide similar attainment/ non-attainment of the 1992 SAV habitat requirements. It is therefore possible to use the midchannel data to determine SAV habitat conditions for a majority of the tidal tributaries and regions of the mainstem Bay analyzed in this study. However, the exceptions in the text above must be considered on a tributary-by-tributary basis.

CHAPTER X

Future Needs for Continued Management Application

This second technical synthesis, which brings together another decade of monitoring and research findings, advances the ability of managers and scientists to assess and diagnose the health of Chesapeake Bay SAV and its supporting habitats. At the same time, the areas requiring further research, assessment and understanding are also brought into sharper focus. Organized by major chapter heading, the following high-priority management needs require that research efforts be directed toward them in the coming years, to set the stage for the next scientific and management synthesis.

MINIMUM LIGHT REQUIREMENTS

There is a general need for better understanding of the minimum light requirements for survival and growth of the diverse set of SAV species that occur in a wide variety of Chesapeake Bay tridal habitats. A coordinated combination of field and laboratory studies is needed to ensure that results will be both precise and representative of conditions in nature. A more in-depth understanding is needed of how SAV minimum light requirements vary with changes in environmental conditions. The need for different sets of minimum light requirements for recovery/recruitment of new SAV beds versus maintenance and protection of existing SAV beds needs to be researched and clarified. The short-term temporal applications of the minimum light requirements need further study to determine the critical length of time under which SAV can recover when faced with extremely low light levels for short periods of time.

WATER-COLUMN CONTRIBUTION TO ATTENUATION OF LIGHT

Continued collection of monitoring data is necessary to track recovery (or further degradation) of the system with respect to the optical water quality targets defined for the various regions using the diagnostic tool. However, it is doubtful that additional monitoring data will improve the ability to derive statistical estimates of specific-attenuation coefficients by regression analysis. Inherent variability in the spectral absorption and scattering properties of the optical water quality parameters, combined with normal uncertainty associated with sampling and laboratory analyses, probably account for the low coefficients of determination and statistically insignificant estimates of some specific-attenuation coefficients. Nevertheless, some attempt to determine regionally based estimates of the water, colored dissolved matter and total suspended solids specific-attenuation coefficients should be made. This is needed because of the pronounced changes in the nature of particulate material that occur from the headwaters to the mouth of major tidal tributaries as well as the mainstem Chesapeake Bay itself. An approach based on direct measurement of particulate absorption spectra and optical modeling likely will be needed to obtain regionally customized diagnostic tools.

EPIPHYTE CONTRIBUTION TO LIGHT ATTENUATION AT THE LEAF SURFACE

While development of the percent light at the leaf surface model was supported by a large data set, there is real need for more research information to support this approach. Field and laboratory studies are needed to better describe relationships among total suspended solids; the biomass of epiphytic algae growing on SAV leaves and the total dry weight of epiphytic material; and between nutrient concentrations and epiphytic algae biomass in various habitats. Further research is also needed to describe the dynamics of how these relationships vary with wind, tides and sediment resuspension. Finally, there is a substantial need for data to allow field assessment of grazer abundance and potential epiphyte grazing rates. Refined application of this model to specific field sites must be attentive to the nutrient-epiphyte relationship that may be affected by other factors, such as grazing and flushing rates. There is a pressing need for field data on these factors to better calibrate these very site-specific applications. Obtaining such information is complicated by the fact that most of these herbivorous grazers are highly mobile, with flexible and diverse food habits.

While results reported here for Chesapeake Bay are encouraging, it remains to be seen how useful the model might be for analyzing other aquatic ecosystems. The general applicability of this approach outside Chesapeake Bay needs to be tested.

PHYSICAL, GEOLOGICAL AND CHEMICAL HABITAT REQUIREMENTS

In those areas where light attenuation remains the key factor in defining potential habitats for the recovery of SAV populations, the plants are largely restricted to shallow water habitats of the Bay mainstem and tidal tributaries as well as the headwaters of feeder streams. Unfortunately, in these same areas the highest levels of wave energy, sediment resuspension and chemical contaminant exposure are most likely to occur. Thus, the aquatic environments most favorable to SAV growth from the perspective of water clarity are not necessarily the most conducive to SAV reestablishment because of these other factors. Therefore, more attention needs to be given to the interactions among the secondary stress factors described in Chapter VI if the management objective of restoring SAV to its historic range within Chesapeake Bay is to be achieved. Finally, care must be exercised in extending the inference of chemical contaminant data generated with one species of SAV to other SAV species. Preliminary evidence is beginning to show significant differences in contaminant sensitivity among the various SAV species of the Bay watershed.

To further define new and refine existing physical, geological and chemical habitat requirements, future research should be focused on:

- the maximum wave exposure tolerated by canopy and meadow formers;
- the appropriateness of including wave mixing depth in determining the minimum depth of distribution;
- possible restrictions imposed by sediment grain size on SAV growth and distribution;
- the maximum amount of sediment organic matter tolerated by different SAV species;
- potential nitrogen toxicity in SAV beds;
- sediment sulfide maxima for the survival of SAV exposed to different light levels; and
- the synergistic effect of multiple chemical contaminants on SAV.

SAV DISTRIBUTION RESTORATION GOALS

There is a need to complete work that is already under way to more fully examine the effects of high wave action on limiting SAV survival and growth within the Chesapeake Bay's shallow water habitats. The results of this research should then be applied to the published Tier II and Tier III distribution restoration targets for making adjustments to any areas considered unlikely to support SAV survival and growth due to high wave action.

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APPENDIX A

Light Requirements for Chesapeake Bay and Other SAV Species

TABLE A-1. Summary of light saturation (I_k) and light compensation point (I_c) for freshwater-oligohaline SAV species.

Species	Experimental design	I_k (μmol m^2 s^{-1})	K_m (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Hydrilla verticillata ([1]dioecious)		600	80	15	Florida	Laboratory	30	AS	Van *et al.* 1976
H. verticillata ([1]monoecious, dioecious)		300-400	40	10	Florida	Laboratory	24 ±2	AS	Steward 1991b
H. verticillata ([1]dioecious)	Growth light varied	150-600 ---------- 150 200 350 600	27-105 ---------- 27 40 55 105	7-20 ---------- 7 10 15 20	Florida	Laboratory --------- grown at 6 μmol 30 μmol 120μmol 300μmol	25	AS	Bowes *et al.* 1977a
Myriophyllum spicatum	Temperature and season varied	341± 134 (mean)		84 ±35 (mean)	Hudson River	River (14% surface light)	AM	AS	Harley and Findlay 1994
M. spicatum		600	120	35	Florida	Laboratory	30	AS	Van *et al.* 1976
M. spicatum			90	38	Lake George, New York	Laboratory	20	AS	Madsen *et al.* 1991
M. spicatum		200			Ontario	Laboratory	25	UL	Lloyd *et al.* 1977

Temp = temperature; AL = apical leaves; AS = apical section; WP = whole plants; UL = underwater leaves; AM = ambient; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.

[1]Monoecious = with stamens and pistils in separate flowers on the same plant; dioecious = unisexual, with the two kinds of flowers on separate plants.

continued

TABLE A-1. Summary of light saturation (I_k) and light compensation point (I_c) for freshwater-oligohaline SAV species (*continued*).

Species	Experimental design	I_k (μmol m^2 s^{-1})	K_m (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
M. spicatum	Growth light varied		164/ 365*		Wisconsin (shade plant/sun plant*)	Laboratory	25	WP AS	Titus and Adams 1979
Elodea canadensis			22	12	Lake George, New York	Laboratory	20	AS	Madsen *et al.* 1991
Vallisneria americana	Temperature and season varied	179±77 (mean)		30±36 (mean)	Hudson River	River (7% surface light)	AM	AS	Harley and Findlay 1994
V. americana	Growth light varied		22	10	Lake George, New York	Laboratory	20	AS	Madsen *et al.* 1991
V. americana		140 (whole plant, day 1)	60/197*		Wisconsin (shade plant/sun plant)*	Laboratory	25	WP AL	Titus and Adams 1979
Ceratophyllum demersum		700	145	35	Florida	Laboratory	30	AS	Van *et al.* 1976
C. demersum	Temperature and season varied	50-350 mean= 138			England	Pond	4-15	AS	Fair and Meeke 1983
C. demersum			23-360		Wisconsin				Titus 1977
C. demersum		210		5-10	Netherlands	Laboratory	20	AS	Best 1986

Temp = temperature; AL = apical leaves; AS = apical section; WP = whole plants; UL = underwater leaves; AM = ambient; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.
[1]Monoecious = with stamens and pistils in separate flowers on the same plant; dioecious = unisexual, with the two kinds of flowers on separate plants.

continued

TABLE A-1. Summary of light saturation (I_k) and light compensation point (I_c) for freshwater-oligohaline SAV species (*continued*).

Species	Experimental design	I_k (μmol m^2 s^{-1})	K_m (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Potamogeton spp			20-40	10-25	Lake George, New York	Laboratory	20	AL or AS	Madsen *et al.* 1991
Potamogeton crispus	Growth light varied	450	207, 245		Italy	Laboratory	25	AS	Baudo 1981
P. crispus		45:130 with epiphytes		22-37 for plant plus epiphytes	Denmark	Laboratory	15-20	AS	San-Jensen and Revsbech 1987
Potamogeton perfoliatus	Temperature and season varied	387±123 (mean)		52±22 (mean)	Hudson R. (15% surface light)	River	AM	AS	Harley and Findlay 1994
P. perfoliatus				25-60	Chesa-peake Bay	Incubator	AM	AS	Goldsborough and Kemp 1988
P. perfoliatus	Growth light varied	450	95, 292		Italy	Laboratory	25	AS	Baudo 1981
Potamogeton pectinatus	Temperature varied		173 312*		New York	Laboratory	30 10*	AS	Madsen and Adams 1989
Hippuris vulgaris, E. canadensis, P. perfoliatus, P. crispus, P. spp.			102-114	5-15	United Kingdom	Laboratory	20	AS	Maberly 1983
Potamogeton amphifolius		200			Ontario	Laboratory	25	UL	Lloyd *et al.* 1977
Cabomba caroliniana		700	160	55	Florida	Laboratory	30	AS	Van *et al.* 1976

Temp = temperature; AL = apical leaves; AS = apical section; WP = whole plants; UL = underwater leaves; AM = ambient; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.
[1]Monoecious = with stamens and pistils in separate flowers on the same plant; dioecious = unisexual, with the two kinds of flowers on separate plants.

continued

TABLE A-1. Summary of light saturation (I_k) and light compensation point (I_c) for freshwater-oligohaline SAV species (*continued*).

Species	Experimental design	I_k (μmol m^2 s^{-1})	K_m (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Najas marina		280		5	Yarkon River, Israel	River	20	WP	Agami *et al.* 1980
Myriophyllum brasilience		250-300		42-45	Florida	Laboratory	30	AS	Salvucci and Bowes 1982
Myriophyllum salsugineum	Temperature and P	41.5-174		2.4-16.9	Australia	Laboratory	15-35	AS	Orr 1988
	measurement varied	93		1.4-1.8			25		

Temp = temperature; AL = apical leaves; AS = apical section; WP = whole plants; UL = underwater leaves; AM = ambient; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.

[1]Monoecious = with stamens and pistils in separate flowers on the same plant; dioecious = unisexual, with the two kinds of flowers on separate plants.

TABLE A-2. Summary of light saturation (I_k) and light compensation point (I_c) for mesohaline-polyhaline SAV species.

Species	Experimental design	I_k (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Zostera marina		100	10	Woods Hole	Field	21-23	LS	Dennison and Alberte 1982
Z. marina	Epiphytes varied	40-125	7-33	Woods Hole	Laboratory	20-25	LS	Mazzella *et al.* 1980
Z. marina		65-120	15-25	Woods Hole	Laboratory	20	LS	Dennison and Alberte 1985
Z. marina	Temperature varied	7 to 120	0.9 to 35	Woods Hole	Laboratory	0-35	LS	Marsh *et al.* 1986
Z. marina	Temperature varied/ plus epiphytes	600-700		North Carolina	*in situ* chambers	15, 22, 29	WP	Penhale 1977
Z. marina	Temperature and season varied	K_m = 300 (12.5 % surface)		Alaska	Lagoon	AM	PR	McRoy 1974
Z. marina		 485 380 230		Denmark	Laboratory lvs w/ep; lvs w/o ep; ep	10	LS	Sand-Jensen 1977
Z. marina		300 est. from K_d/150 from PI curves		Long Island Sound	Field Laboratory		WP LS	Koch and Beer 1996
Z. marina	Temperature varied	28-46 mean = 37		Chesapeake Bay	Laboratory	Various	LT	Evans *et al.* 1986
Z. marina		35 ±17		San Francisco Bay	Laboratory	15	LS	Zimmerman *et al.* 1991
Z. marina	Temperature varied seasonally	80-385; mean= 238 ±117	25-417	Chesapeake Bay	*in situ* dome incubations	1-28 for I_k; 6-28 for I_c	WP	Wetzel and Penhale 1983
Z. marina		208	25	Great Britain	Laboratory	15	LS	Drew 1979

Temp = temperature; AM = ambient; lvs = leaves; LS = leaf sections; LT = leaf tips; WP = whole plants; ep = epiphytes; ES = entire shoot; PR plant with roots; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.

continued

TABLE A-2. Summary of light saturation (I_k) and light compensation point (I_c) for mesohaline-polyhaline SAV species (*continued*).

Species	Experimental design	I_k (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Phyllospadix torreyi		150	21	Great Britain	Laboratory	15	LS	Drew 1979
Cymodocea nodosa		158	17	Great Britain	Laboratory	25	LS	Drew 1979
Zostera angustifolia		133	12	Great Britain	Laboratory	10	LS	Drew 1979
Halophila stipulacea		83	8	Great Britain	Laboratory	25	lvs	Drew 1979
Posidonia oceanica		108	7	Great Britain	Laboratory	17	LS	Drew 1979
Thalassia testudinum *Halodula wrightii* *Syringodium filiforme*			15/33/14 corrected for respiration 40/65/35	Florida Bay	Laboratory	25-30	shoots	Fourqurean and Zieman 1991a
Thalassia testudinum	Tested PI models	357-438		plants from Florida Bay	Laboratory	25-30	shoots	Fourqurean and Zieman 1991b
T. testudinum	Compared sensors, whole plants vs. leaves	290 85	112 30	Texas	*in situ* Laboratory	AM	WP lvs	Herzka and Dunton 1997
H. wrightii	Seasonal	127-365 mean = 308	28-235 mean = 73	Laguna Madre, Texas	*in situ*	AM	WP	Dunton and Tomasko 1991
H. wrightii	Compared lab and field/seasonal	Field: 189-453 seasonal mean = 319; Mean at 29 °C = 349±27/ Lab: 101±4	Field: 37-177 seasonal mean = 85: Mean at 29 °C = 111±21/ Lab: 22±2	Laguna Madre, Texas	Field (*in situ*) Laboratory	12-30 Field/ 29 Lab	Field: WP/ Lab: LS	Dunton and Tomasko 1994

Temp = temperature; AM = ambient; lvs = leaves; LS = leaf sections; LT = leaf tips; WP = whole plants; ep = epiphytes; ES = entire shoot; PR plant with roots; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.

continued

TABLE A-2. Summary of light saturation (I_k) and light compensation point (I_c) for mesohaline-polyhaline SAV species.

Species	Experimental design	I_k (μmol m^2 s^{-1})	I_c (μmol m^2 s^{-1})	Location	Venue	Temp °C	Plant part	Reference
Ruppia maritima	Temperature varied	45-72 mean = 57		Chesapeake Bay	Laboratory	Various	LT	Evans *et al.* 1986
R. maritima		396-1200	11-88	Plants from North Carolina and Florida	Laboratory	14,22,30	LS	Koch and Dawes 1991
R. maritima	Temperature varied seasonally	150-561	133-311	Chesapeake Bay	*in situ* dome incubations	1-28 for I_k; 6-28 for I_c	WP	Wetzel and Penhale 1983
Cymodocea nodosa; Posidonia oceanica	Temperature varied	83-125		Malta	Laboratory and *in situ*	14.5-25	LS	Drew 1978

Temp = temperature; AM = ambient; lvs = leaves; LS = leaf sections; LT = leaf tips; WP = whole plants; ep = epiphytes; ES = entire shoot; PR plant with roots; I_k = irradiance at saturation; I_c = compensation point; K_m = 1/2 saturation constant or 1/2 P_{max}.

TABLE A-3. Summary of Chesapeake Bay SAV species light limitation studies involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations.

Species	Light Measurements	Maximum Depth of Growth (Z_{max}) (m)	Light at Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
Hydrilla verticillata	PAR–photometer		5 (<100 μmol m^{-2} s^{-1})	Florida (outside aquarium)	Ambient	Steward 1991b
H. verticillata	Intermittent PAR measurements–photometer	4.6-1.8	~5	Lake Tutira, New Zealand	Ambient	Johnstone and Robinson 1987
H. verticillata	Secchi depth and PAR (10 lakes)/ regression used to estimate 16 other lakes		0.46-5.4	Florida lakes	Ambient	Canfield *et al.* 1985
Elodea canadensis	Clear midsummer day–photometer	12	10	Lake George, New York	>20	Sheldon and Boylen 1977
E. canadensis	Intermittent PAR measurements–photometer	1.8- 6.7	<5	Lake Tutira, New Zealand	Ambient	Johnstone and Robinson 1987
E. canadensis	Photometer (early model)		<2	Lake Erie	23-26	Meyer *et al.* 1943
E. canadensis	Semi-monthly or monthly PAR measurements	12-14	0.5-1	Shoal Lake, Manitoba, Ontario	18.7 in Aug.	Pip and Simmons 1986
E. canadensis	Optical measurements	4.5	4.5	Trout Lake, Wisconsin		Hutchinson 1975
Vallisneria americana	Optical measurements	4.5	4.5	Trout Lake, Wisconsin		Hutchinson 1975
V. americana	Clear midsummer day–photometer	7	~20	Lake George, New York	>20	Sheldon and Boylen 1977

continued

TABLE A-3. Summary of Chesapeake Bay SAV species light limitation studies involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations (*continued*).

Species	Light Measurements	Maximum Depth of Growth (Z_{max}) (m)	Light at Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
V. americana	Photometer (early model)		<2	Lake Erie	23-26	Meyer *et al.* 1943
V. americana		1.34	2.4-3.7 (30.5 - 37.9 μmol m^{-2} s^{-1})	Wisconsin Lake/Laboratory	Ambient	McAllister 1991
V. americana tubers planted different depths	Photometer– continuous monitoring over growing season	0.5 1.0 1.5	9 depth new tubers formed	Lake Onalaska, Wisconsin	Ambient	Kimber *et al.* 1995
Potamogeton pectinatus	Not documented	3.1	5	Swartvlei system (estuary-lake complex) in South Africa–brackish	Ambient	Howard-Williams and Liptrot 1980
P. pectinatus	Optical measurements	2.5	14	Trout Lake, WI		Hutchinson 1975
P. pectinatus	Clear midsummer day–photometer	3	~52	Lake George, New York	>20	Sheldon and Boylen 1977
Potamogeton crispus	Clear midsummer day–photometer	3	~52	Lake George, New York	>20	Sheldon and Boylen 1977
Heteranthera dubia	Photometer (early model)		<2	Lake Erie	23-26	Meyer *et al.* 1943
Potamogeton perfoliatus	Secchi depth		4	England		Pearsall 1920
P. perfoliatus	Clear midsummer day–once–photometer	7	20	Lake George, New York	>20	Sheldon and Boylen 1977
Najas flexilis	Clear midsummer day–once–photometer	9	17	Lake George, New York	>20	Sheldon and Boylen 1977
N. flexilis	Photometer (early model)		2-3	Lake Erie	23-26	Meyer *et al.* 1943

continued

TABLE A-3. Summary of Chesapeake Bay SAV species light limitation studies involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations (*continued*).

Species	Light Measurements	Maximum Depth of Growth (Z_{max}) (m)	Light at Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
Naja flexilis	Semi-monthly or monthly PAR measurements–photometer	12-14	0.5-1	Shoal Lake, Manitoba-Ontario	18.7 in Aug.	Pip and Simmons 1986
N. flexilis	Optical measurement	5.5	3.1	Trout Lake, WI		Hutchinson 1975
Ceratophyllum demersum	Optical measurement	6.5	1.8	Trout Lake, WI		Hutchinson 1975
C. demersum	Semi-monthly or monthly PAR measurements–photometer	12-14	0.5-1	Shoal Lake, Manitoba-Ontario	18.7 in Aug.	Pip and Simmons 1986
C. demersum	Secchi depth and PAR (10 lakes)/ regression used to estimate 16 lakes		1.1-3.4	Florida	Ambient	Canfield *et al.* 1985
Heteranthera dubia	Clear midsummer day–photometer	5	38	Lake George, NY	>20	Sheldon and Boylen 1977
P. perfoliatus *P. pectinatus* *V. americana*	Photometer (early model)	transplants–no survival	2-8 at 1 m	Back Bay, North Bay, Currituck Sound	Ambient	Bourn 1932
Z. marina	Secchi depth		almost same as Secchi depth, about 10%			Ostenfield 1908
Z. marina	Photometer weekly, Feb.-Dec.	0.5 1.0 1.5 2.0 2.0	21.2 11.1 5.8 4.1 5.0	San Francisco Bay	Ambient	Zimmerman *et al.* 1991

continued

TABLE A-3. Summary of Chesapeake Bay SAV species light limitation studies involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations.

Species	Light Measurements	Maximum Depth of Growth (Z_{max}) (m)	Light at Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
Z. marina	Photometer–average K_d over year	6	18.6	Woods Hole, MA	Ambient	Dennison 1987
Z. marina	Photometer monthly (May-October)	1 4	35.7 15	Long Island Sound, NY	Ambient	Koch and Beer 1996
Z. marina	Year-round measurements of light intensity–photometer	1.5	20 (summer/fall); 25-30 (winter/spring)	York River, VA	Ambient	Moore 1991

TABLE A-4. Summary of studies of SAV species light limitation involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations. Freshwater-polyhaline species not found in the Chesapeake Bay.

Species	Light Measurements	Maximum Depth of Growth Z_{max} (m)	Light of Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
Elodea baldwinii	Secchi depth measured once at peak abundance		4.8± 2.185	Florida	No data	Canfield *et al.* 1985
Utricularia vulgaris	Secchi depth measured once at peak abundance		6.2± 2.1	Florida	No data	Canfield *et al.* 1985
Hippuris vulgaris	PAR measured on sunny day in June	6	15 (100 μmol m^{-2} s^{-1})	Scotland	15	Bodkin *et al.* 1980
Potamogeton berchtoldii			2-15	England		Hutchinson 1975
Potamogeton praelongus			2-10	England		Hutchinson 1975
Potamogeton alpinus			4-40	England		Hutchinson 1975
Potamogeton spp.	Optical measurements	0.5-6	2.4-62	Trout Lake, WI		Hutchinson 1975
Myriophyllum spp.		2.5-4	5.9-10	Trout Lake, WI		Hutchinson 1975
Thallasia testudinum *Halodule wrightii* *Syringodium filiforme*	Whole plant PI curves–calculated		10-20	Florida Bay	Ambient	Fourqurean and Zieman 1991b
T. testudinum; H. wrightii; S. filiforme	Light depth profiles for 20 months–photometer–PAR		15	Laguna Madre, TX	Ambient	Onuf 1991

TABLE A-4. Summary of studies of SAV species light limitation involving measurements or estimates of percent of surface light at maximum depth (Z_{max}) from field observations. Freshwater-polyhaline species not found in the Chesapeake Bay (*continued*).

Species	Light Measurements	Maximum Depth of Growth Z_{max} (m)	Light of Maximum Depth (% of surface irradiance)	Location	Temp °C	Reference
H. wrightii *S. filiforme*	Light profiles and depth distribution–photometer	2-2.75	24-37	Hobe Sound, Jupiter Sound, NC	Ambient	Kenworthy and Fonseca 1996
H. wrightii, *S. filiforme*	Light profiles and depth distribution–photometer		>10-15	Indian River Lagoon, FL	Ambient	Kenworthy *et al.* 1991

APPENDIX B

The Role of Chemical Contaminants as Stress Factors Affecting SAV

TABLE B-1. Representative evaluation of the role of chemical contaminants as stess factors affecting SAV.

Plant/Animal Species	Test System	Test Type	Contaminants	End Points	Reference
Ceratophyllum, *Zizania*, Macroinverts (3)	Field mesocosm	Single chemical	Herbicide Atrazine	Nutrients, periphyton biomass and productivity resp., and macrophyte growth	Detenbeck *et al.* 1996
Elodea densa	Microcosm	Single chemical	Herbicide Isoproturon	PSII chlorophyll Fluorescence (induction) Bioaccumulation	Grouselle *et al.* 1995
E. densa *Ceratophyllum*	Ambient Mesocosms	Single chemical	Atrazine	Nutrient levels periphyton biomass	Detenbeck *et al.* 1996
Elodea nuttallii	Mesocosms	Single chemical	Insecticide Dursban (chlorpyrifos)	Plant biomass Macrophyte populations	Brock *et al.* 1992
Hydrilla verticillata	Microcosms	Lab	Anthracene sulfometuron methyl cadmium, chromium, copper, manganese, selenium	Peroxidase activity growth (cm)	Byl *et al.* 1994
H. verticillata	Field Mesocosms	Single chemical + adjuvants	Diquat, diquat + nalquatic Herbicide diquat +submerge Rhodamine	Vertical water-column distribution, HPLC	Langeland *et al.* 1994

continued

TABLE B-1. Representative evaluation of the role of chemical contaminants as stess factors affecting SAV (*continued*).

Plant/Animal Species	Test System	Test Type	Contaminants	End Points	Reference
H. verticillata	Microcosm	Single chemical Heavy metal	Lead	Conc. cysteine, thiol, glutathione, phytochelatins	Gupta *et al.* 1995
H. verticillata *Vallisneria spiralis*	Axenic	Single chemical	Lead Nitrate reduction	Bioaccumulation chlorophyll, protein	Gupta and Chandra 1994
H. verticillata	Microcosms	Single chemical Heavy metal	Cadmium 1.0μm-25.0 μm	Protein, cysteine nitrate reductase, chlorophyll content	Garg 1997
H. verticillata	Polargraphic & fluorometric	Single chemical	Paraquat	O_2 evolution	Mishra and Sabat 1995
H. verticillata	Field	Single chemical	Acrolein	Biomass	Anderson and Dechoretz 1982
H. verticillata	Axenic	Single chemical sediment & water	Atrazine, lindane, chlordane	(BCF) bioconcentration factors, Chemical translocation	Hinman and Klaine 1992
H. verticillata *Myriophyllum spicatum*	Flask Microcosm	Single chemical	Flurprimidol, paclobutrazol, uniconazote	Height, photosynthesis, respiration, chlorophyll	Netherland and Lembi 1992
M. spicatum	Axenic	Single chemical	2,4-D, Atrazine, glyphosate, linuron, thidiazuron	Buds, leaves, roots, & branches	Christopher and Bird 1992

continued

TABLE B-1. Representative evaluation of the role of chemical contaminants as stess factors affecting SAV (*continued*).

Plant/Animal Species	Test System	Test Type	Contaminants	End Points	Reference
M. spicatum	Mesocosm	Single chemical	Heavy metal cadmium	Biomass (dry wts.) Bioacc (spectophotometry)	Sajwan and Ornes 1996
M. spicatum	Axenic, Mesocosm	Single chemical	Herbicides simazine, Atrazine, metrobuzin terbacil, diuron	O_2 evolution (BOD)	Selim *et al.* 1989
Posidonia oceanica	Field collections	Single chemical	Cadmium	T bars content, oxidative metabolism	Hamoutene *et al.* 1996
Potamogeton folius	Field	Ambient sediment, water	PCBs, cadmium, copper, chromium, cobalt, manganese, organic carbon inputs, mercury, nickel, uranium, zinc contaminant sediment to plant ratio	Bioaccumulations	Stewart *et al.* 1992
Potamogeton nodosus	Mesocosm	Single chemical	Bensulfuron	Number of winter buds formed	Anderson 1989
Potamogeton pectinatus	Mesocosm	Multichemical	Chlorsulfuron DPX 5648	Fresh wt., dry wt., length	Anderson and Dechoretz 1982
P. pectinatus	Heterotrophic microcosms autotrophic	Single chemical	Atrazine, paraquat, glyphosate, alachlor	Biomass	Fleming *et al.* 1991

continued

TABLE B-1. Representative evaluation of the role of chemical contaminants as stess factors affecting SAV (*continued*).

Plant/Animal Species	Test System	Test Type	Contaminants	End Points	Reference
P. pectinatus	BOD	Single chemical	Acifluorfen, alachlor, Atrazinee, cyanazine, glyphosate, linuron, metolachlor, metribuzin, paraquat, simazine, 2, 4-D	O_2 evolution IC50	Fleming *et al.* 1993
P. pectinatus	Microcosms autotrophic	Single chemical	Atrazine	O_2 evolution biomass	Fleming *et al.* 1988
P. pectinatus	Microcosm	Single chemical	Atrazine	Fresh wt., dry wt., & rhizome tips	Hall *et al.* 1997
P. pectinatus	BOD Microcosm	Subchronic Toxicity	Herbicide	Fresh wt., dry wt., rhizome tips & O_2	Hall *et al.* 1997
P. pectinatus *Myriophyllum sibiricum*	Field	Single chemical, Multichemical	Clopyralid, 2,4-D, Picloram, Tordon	Plant weight Flower & turion production	Forsyth *et al.* 1997
P. pectinatus (turions)	Mesocosms	Single chemical	Fluridone	Plant weight, lengths, turions/plant	Spencer *et al.* 1989
Vallisneria americana	Field	Acute & chronic	Organochlorine	Multiple	Lovett-Doust *et al.* 1994
V. americana	Mesocosm	Ambient (sediment)	Sediments, unspecified contaminants	Biomass accumulation	Biernacki *et al.* 1997

APPENDIX C

SAS Code Used to Calculate PLL from K_d, TSS, DIN and DIP

SAS Code Used to Calculate PLL from K_d, TSS, DIN and DIP

```
*calculate PLL;

*Z IS RESTORATION DEPTH IN METERS, vary among 1, 0.5, 0.25, & 0;
*halfgtr is half the greater tropic or diurnal tidal range in meters,
see listing in other table;

Z =1 + halfgtr;
OD = KD*Z;

*CALC BEM;
IF OD NE . THEN DO;
IF OD < 5.8 THEN  BEM = 2.2 - (0.251*(OD**1.23));
ELSE BEM = 0.01;
END;

IF din ne . and din<(dip*7.2) then nutr =(din*71.4);
IF dip ne . and din>=(dip*7.2) then nutr = (dip*515.9);

KNOD = -2.32 * (1 - 0.031*(OD**1.42));

EPBIOSAV = BEM / (1 + (208*(nutr**KNOD)));

MGCHL = (EPBIOSAV * 5);

EPDWSAV = (0.832 * MGCHL) + (0.107 * TSS);

*NExt line had to be edited to avoid Div. by 0 error;

if epdwsav > 0 then CHLDW = MGCHL / EPDWSAV;

CHLCMSQ = MGCHL / 3.7;

KEXT  = -0.07 - (0.322 * CHLDW**(-0.88));

PCT_REDU = EXP(KEXT * CHLCMSQ);

PLL = EXP((-Z * KD) + (KEXT * chlCMSQ));

*>>need the if statement for comparing pll to plw, otherwise can use  second equation;
if (din ne . and dip ne . and tss ne .) then PLW = EXP(-Z*KD);
*PLw = EXP(-Z*KD);
*END OF PLL.FRAG;
```

APPENDIX D

SAV Depth, Area and Water Quality Data Used and Details of Statistical Analysis Performed

SAV AREA BY DEPTH AND WEIGHTED MEAN DEPTH

SAV area by depth data were examined to see if they were correlated with water quality data. This was done by generating depth contours at 0.5, 1 and 2 meters MLLW and overlaying SAV polygons on them. The SAV area within four depth ranges was calculated for each Chesapeake Bay Program segment and year, and the areas were converted to percentages by dividing each by the total area in that segment and multiplying by 100. The depth ranges, area variables and percent variables for each are listed in Table D-1.

These areas were also used to calculate a weighted mean SAV depth for each segment and year (SAVDEP). This was done with the usual formula for weighted mean, multiplying the area in each depth range by the midpoint of each range, summing them and dividing their sum by the total area:

SAVDEP = [(AREA05)*0.25 + (AREA1)*0.75 + (AREA2)*1.5 + (AREAGT2)*2.5] / (Total SAV area)

Since the Area > 2 category has no upper bound, 2.5 meters was chosen as the midpoint, assuming that very little of the mapped SAV was growing in water more than 3 meters deep MLLW. This assumption was based on ground truth observations that SAV is rarely found below this depth and the limited ability to see below this depth in aerial photos taken in the normally turbid Chesapeake. This mean depth was used in Spearman rank correlations with water quality parameters, along with the four percentages in different depth categories.

SAV AREA DATA AND GROWTH CATEGORIES

SAV area by Chesapeake Bay Program segment came from the Chesapeake Bay SAV aerial survey. The latest table of hectares by segment by year was downloaded from the VIMS web page (http://www.vims.edu/bio). SAV growth categories were used for some analyses, which represented average conditions over all years with SAV area data. For the York and Choptank rivers, the same 'Persistent,' 'Fluctuating' and 'None' categories were used that were used before (Batiuk *et al.* 1992). These categories were based on observations of the persistence over time of either natural or transplanted SAV near the monitoring stations. For the Chesapeake Bay SAV Aerial Survey data, the three different categories for SAV area by USGS quad were applied to SAV area by CBP segment instead of quad, using 1978-97 SAV hectares by segment by year. The three categories were expanded to five and were considered equivalent to the categories used in Batiuk *et al.* (1992), as show in Table D-2.

Adding two more categories to the ones defined by Hagy (unpublished data) helped separate the 'best' and 'worst' segments from the others. These were the 'Always Abundant' and 'Always None' categories respectively. The results of this analysis for each Chesapeake Bay Program segment are shown in Table D-3.

WATER QUALITY DATA USED

Data used for SAV habitat requirements were from surface samples (Layer = 'S') from selected Chesapeake Bay Water Quality stations in each segment.

TABLE D-1. SAV depth ranges and variable names.

Depth range	Area variable	Percent variable
Less than 0.5 meters deep	AREA05	PCT05
0.5-1 meter deep	AREA1	PCT1
1-2 meters deep	AREA2	PCT2
Greater than 2 meters deep	AREAGT2	PCTGT2

TABLE D-2. Five categories used for characterizing SAV growth status by segment based on 1978-1997 aerial survey data.

New category (based on aerial survey data)	Criteria used for category (using SAV area by year by segment)	SAV TSI growth category (based on transplant success)
Always Abundant (AA)	Minimum > 200 ha	Persistent
Always Some (AS)	Minimum > 0	Persistent
Sometimes None (SN)	Minimum = 0 and Median > 0	Fluctuating
Usually None (UN)	Median = 0 and Maximum > 0	None
Always None (AN)	Maximum = 0	None

When there was more than one station per segment, stations that were too far from SAV were dropped from the analysis (Table D-5). Nearshore data collected in the York and Choptank rivers for the first SAV Technical Synthesis (Batiuk *et al.* 1992) were also used. Volunteer monitoring data were not used because they were only available for a few years and segments.

Data were used only from the SAV growing seasons: April-October for tidal fresh, oligohaline and mesohaline regimes and March-May and September-November in polyhaline. Raw data from all stations used in each segment were used for the Wilcoxon test. Monthly means were not calculated since each month had two samples (where sampling is twice a month) and this would reduce the sample size. For consistency, light attenuation (K_d) was calculated from K_d = 1.45/Secchi even if K^d data from light measurements were available.

TESTING ATTAINMENT OF HABITAT REQUIREMENTS

The attainment of SAV habitat requirements was tested by segment or station and year with the Wilcoxon one-sample test, using the difference between each observation and the habitat requirement for that salinity regime as the data for the test. A custom SAS program to perform the test was written for this application (see Appendix C). When done by segment, data from all the stations used in that segment were used for the test without any averaging, so the sample size was larger if there were more stations. The results were classified in three categories using a two-tailed significance level (P) of 0.05:

Met: median was significantly below the requirement

Borderline: median did not differ significantly from requirement

Not met: median was significantly above the requirement

This test was more sensitive to the consistency of the differences (positive or negative) than to their magnitude.

Tidal range data were used to adjust the restoration depth (Z). This number is critical to both PLW and PLL calculations since it determines the path length for light passing through the water, and thus how much the light is attenuated passing through the water. For any two sites, the one with greater tidal range will on average have more water above the 1 meter depth contour which is referenced to MLLW, the bottom elevation for the tidal range used (semi-diurnal or greater tropic range).

TABLE D-3. New CBP segments classified according to SAV growth category (GROWTH) using 1978-1997 SAV area data: MAX = maximum, MED = median, MIN = minimum (hectares).

SEGMENT	SAVH_MAX	SAVH_MED	SAVH_MIN	GROWTH
APPTF	0	0	0	AN
BACOH	0	0	0	AN
BIGMH	192.12	156.98	0	SN
BOHOH	15.09	1.67	0	SN
BSHOH	39.04	0.26	0	SN
C&DOH	0.62	0	0	UN
CB1TF	2714.04	2076.51	833.98	AA
CB2OH	127.49	17.69	4.02	AS
CB3MH	554.83	327.82	22.21	AS
CB4MH	102.57	5.63	0	SN
CB5MH	1666.81	751.63	275.12	AA
CB6PH	512.84	367.43	241.92	AA
CB7PH	4597.91	3442.21	2452.12	AA
CB8PH	4.4	0	0	UN
CHKOH	89.17	0	0	UN
CHOMH1	2792.59	1168.68	57.75	AS
CHOMH2	94.31	0	0	UN
CHOOH	0	0	0	AN
CHOTF	0	0	0	AN
CHSMH	1050.3	309.18	32.45	AS
CHSOH	0	0	0	AN
CHSTF	0	0	0	AN
CRRMH	178.46	36.85	0	SN
EASMH	1848.32	781.91	67.93	AS
ELIPH	0	0	0	AN
ELKOH	355.81	81.01	0.87	AS
FSBMH	25.88	1.32	0	SN
GUNOH	637.36	74.95	0	SN
HNGMH	1845.44	893.09	13.42	AS
JMSMH	1.05	0	0	UN
JMSOH	0	0	0	AN
JMSPH	75.74	3.68	0	SN
JMSTF	0	0	0	AN
LCHMH	529.39	102.7	18.35	AS
LYNPH	43.2	29.65	0	SN
MAGMH	141.27	7.3	0	SN
MANMH	156.74	90.73	0	SN
MATTF	60.65	33.24	0	SN
MIDOH	117.37	16.47	0	SN
MOBPH	4465.86	4134.99	2736.2	AA
MPNOH	0	0	0	AN
MPNTF	0	0	0	AN
NANMH	0	0	0	AN
NANOH	0	0	0	AN
NANTF	0	0	0	AN
NORTF	7.96	0.17	0	SN
PATMH	48.96	0	0	UN
PAXMH	53.74	1.27	0	SN
PAXOH	40.08	0	0	UN
PAXTF	63.93	0	0	UN
PIAMH	438.2	143.16	10.23	AS
PISTF	319.35	54.3	0	SN
PMKOH	0	0	0	AN
PMKTF	0	0	0	AN
POCMH	783.8	597.92	87.3	AS
POCOH	0	0	0	AN
POCTF	0	0	0	AN
POTMH	666.84	109.42	43.12	AS
POTOH	1501.15	1121.46	217.09	AA
POTTF	1874.69	1209.05	0	SN
RHDMH	5.92	0	0	UN
RPPMH	348.69	31.44	7.75	AS
RPPOH	0	0	0	AN
RPPTF	0	0	0	AN
SASOH	179.79	36.75	6.41	AS
SBEMH	0	0	0	AN
SEVMH	133.78	0	0	UN
SOUMH	20.59	0	0	UN
TANMH	7330.38	5094.61	2927.4	AA
WICMH	0	0	0	AN
WSTMH	46.65	0	0	UN
YRKMH	0	0	0	AN
YRKPH	339.5	269.68	106.68	AS

The tidal range data used was obtained from the "benchmark" data on the NOAA home page: http://www.opsd.nos.noaa.gov/bench.html

The station listings for Maryland and Virginia on this web page include the number we want, MHHW elevation, which is the same as the semi-diurnal range or greater tropic range (MHHW-MLLW) since MLLW is zero in the NOAA benchmark data. However, there do not appear to be any benchmark MHHW data for the following rivers or areas:

Upper Western Shore Maryland-Bush, Gunpowder, Middle, Back rivers

Lower Western Shore Maryland-Rhode, West rivers and Patuxent above Solomons, Potomac-from Colonial Beach upriver to DC

Eastern Shore-Wicomico, Pocomoke rivers (Maryland)

VA Western shore-Rappahannock and York rivers above their mouths

The published commercial tide tables have data for at least one site in or near all of these rivers. However the tide table (Reed's) lists the "spring range," not the semi-diurnal range. The spring range in this table differs from the semi-diurnal range at the benchmark stations as follows:

1. Spring range > semi-diurnal range, south of a line running diagonally across the Bay, from Fishing Bay (Eastern Shore) SW to Smith Point (just South of Potomac). Differences about 0.2-0.3 feet.
2. Semi-diurnal range > spring range, north of this line, differences about 0.1-0.5 feet (larger differences farther north).

To fill in the spatial gaps in benchmark data, we adjusted spring ranges to estimate semi-diurnal ranges. Since the relationship varies spatially, but has a strong positive correlation (R-square for linear regression was 78 percent), we adjusted the spring range to approximate the semi-diurnal range as follows: Estimated semi-diurnal range at site without benchmark data equal spring range at that site * (semi-diurnal range at nearest benchmark site/spring range at benchmark site).

For example, for the Gunpowder River, closest benchmark is Tolchester (Eastern shore mainstem), estimated semi-diurnal range = 1.4 ft * (1.74/1.4) = 1.74 ft., since spring range is the same at both sites; for West River, using South River benchmark, estimated semi-diurnal range = 1.0 * (1.48/1.1) = 1.35 ft. We used this method to estimate semi-diurnal range from spring range for one point near the middle of any segments that lacked benchmark data. If no spring range data were available (e.g. the Bush River) the closest point with spring range data was used. The resulting semi-diurnal tidal ranges in feet and half tidal range in meters are listed in Table D-4.

TABLE D-4. Semi-diurnal tidal range for 77 CBP segments, calculated from NOAA data.

SEGMENT	Semi-diurnal range (ft)	Half range (meters)	SEGMENT	Semi-diurnal range (feet)	Half range (meters)
APPTF	3.5475	0.54243	MIDOH	1.84333	0.28186
BACOH	1.58	0.24159	MOBPH	2.65	0.4052
BIGMH	2.16	0.33028	MPNOH	3.4428	0.52642
BOHOH	2.68	0.40979	MPNTF	3.9724	0.6074
BSHOH	1.99579	0.30517	NANMH	2.34	0.3578
CB1TF	2.37	0.36239	NANOH	2.17286	0.33224
CB2OH	1.74	0.26606	NANTF	2.50714	0.38336
CB3MH	1.72	0.263	NORTF	2.45667	0.37564
CB4MH	1.6	0.24465	PATMH	1.62	0.24771
CB5MH	1.41867	0.21692	PAXMH	1.51	0.23089
CB6PH	1.86	0.2844	PAXOH	2.32308	0.35521
CB7PH	2.53	0.38685	PAXTF	3.25231	0.49729
CB8PH	3.255	0.49771	PIAMH	1.26	0.19266
CHKOH	2.3876	0.36508	PISTF	2.968	0.45382
CHOMH1	1.76	0.26911	PMKOH	2.7366	0.41844
CHOMH2	2.05	0.31346	PMKTF	2.8248	0.43193
CHOOH	2.17059	0.33189	POCMH	2.555	0.39067
CHOTF	2.29118	0.35033	POCOH	2.64625	0.40463
CHSMH	2.15	0.32875	POCTF	1.825	0.27905
CHSOH	2.65588	0.4061	POTMH	1.755	0.26835
CHSTF	3.54118	0.54146	POTOH	1.3479	0.2061
CRRMH	1.44	0.22018	POTTF	2.57818	0.39422
EASMH	1.745	0.26682	RHDMH	1.43	0.21865
EBEMH	3.2455	0.49625	RPPMH	1.74	0.26606
ELIMH	3.15	0.48165	RPPOH	1.62	0.24771
ELIPH	2.9591	0.45246	RPPTF	1.98	0.30275
ELKOH	2.68	0.40979	SASOH	2.15	0.32875
FSBMH	2.36	0.36086	SBEMH	3.3	0.50459
GUNOH	1.84333	0.28186	SEVMH	1.43	0.21865
HNGMH	1.57333	0.24057	SOUMH	1.43	0.21865
JMSMH	2.75	0.42049	TANMH	2.04	0.31193
JMSOH	2.18	0.33333	WBEMH	2.9591	0.45246
JMSPH	2.8	0.42813	WBRTF	3.3	0.50459
JMSTF	2.15	0.32875	WICMH	2.42357	0.37058
LAFMH	2.9591	0.45246	WSTMH	1.3	0.19878
LCHMH	1.87733	0.28705	YRKMH	3.0014	0.45893
LYNPH	1.68	0.25688	YRKPH	2.645	0.40443
MAGMH	1.49	0.22783			
MANMH	2.16	0.33028			
MATTF	1.86632	0.28537			

TABLE D-5. Mainstem Chesapeake Bay Water Quality Monitoring Program stations used in analysis of the SAV habitat requirements.

Segment	Stations used	Notes
CB1TF	CB1.1, CB2.1	Only stations in segment, all used
CB2OH	CB2.2, CB3.1	Only stations, all used
CB3MH	CB3.2, CB3.3W, CB3.3E	Dropped CB3.3C (see below)
CB4MH	CB4.1W, CB4.2E, CB4.3E, CB4.4	Dropped all stations in center of Bay (ending in 'C') and all but one of the west ('W') stations, because they do not characterize SAV habitat
CB5MH	CB5.1, CB5.2, CB5.3, CB5.4, CB5.4W, CB5.5	Only stations (none are very close to SAV habitat but no other data are available)
FSBMH	EE3.0	Only station
TANMH	EE3.1, EE3.2	EE3.4 dropped because it does not characterize SAV habitat
POCMH	EE3.3	Only station in segment
WE4PH	WE4.1, WE4.2, WE4.3, WE4.4	Only stations, all used
CB6PH	CB6.3	CB6.1, CB6.2 and CB6.4 dropped because they do not characterize SAV habitat
CB7PH	EE3.5, CB7.1, CB7.1S, CB7.2E	CB7.1N, CB7.2,, CB7.3E, CB7.3, and CB7.4N dropped because they do not characterize SAV habitat

Note: Data from all of the Chesapeake Bay Water Quality Monitoring Program's tidal tributary monitoring stations were used. In addition, data from segment CB8PH, mouth of Chesapeake Bay, were dropped from analyses relating SAV growth categories or SAV area to water quality, because none of the water quality monitoring stations in that segment characterize the small tidal creek (Little Creek) that contains the only SAV found in that segment.

APPENDIX E

Spearman Rank Correlations between Chesapeake Bay Water Quality Monitoring Program Data and Measures of SAV Area

TABLE E-1. Tidal fresh Spearman rank correlations between water quality parameters from Chesapeake Bay Program midchannel water quality monitoring stations over the whole growing season, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	**Tidal fresh (April-October)**					**KEY**
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	-0.0596	-0.06005	-0.06537	-0.03866	0.07773	r_s
	0.4906	0.4874	0.4496	0.6699	0.3684	P
	136	136	136	124	136	N
PLW(1+)	0.10356	0.10757	0.11983	0.11201	-0.06748	r_s
	0.2524	0.2344	0.185	0.2397	0.4564	P
	124	124	124	112	124	N
PLL(1+)	0.14137	0.14702	0.16066	0.15532	-0.07284	r_s
	0.1173	0.1032	0.0747	0.102	0.4214	P
	124	124	124	112	124	N
TSS	*-0.17325*	*-0.18466*	-0.17423	*-0.19696*	0.00593	r_s
	0.0543	*0.0401*	0.053	*0.0374*	0.9479	P
	124	*124*	124	*112*	124	N
CHLA	0.08112	0.0791	0.09939	0.11388	-0.04165	r_s
	0.3425	0.3547	0.2444	0.2024	0.6264	P
	139	139	139	127	139	N
DIP	-0.15833	*-0.18026*	*-0.21387*	*-0.20039*	0.10017	r_s
	0.0627	*0.0337*	*0.0115*	*0.0239*	0.2407	P
	139	*139*	*139*	*127*	139	N
DIN	*0.5474**	*0.53887**	*0.54511**	*0.54664**	0.08264	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.3335	P
	139	*139*	*139*	*127*	139	N

KEY: PCT_T2 = SAVH/Tier II area*100, PCT_T3 = SAVH/Tier III area*100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; P r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). *Statistically significant but not in the expected direction; probably spurious (no DIN requirement).

TABLE E-2. Tidal fresh Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the spring, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Tidal fresh (April-June)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	0.00761	0.01365	0.01317	0.02831	0.02677	r_s
	0.9302	0.8752	0.8795	0.7559	0.7579	P
	135	135	135	123	135	N
PLW(1+)	0.03689	0.03551	0.04127	0.03922	-0.02224	r_s
	0.6854	0.6966	0.6504	0.6828	0.8071	P
	123	123	123	111	123	N
PLL(1+)	0.07907	0.08164	0.08834	0.08791	-0.016	r_s
	0.3847	0.3693	0.3312	0.3589	0.8606	P
	123	123	123	111	123	N
TSS	-0.04713	-0.05391	-0.0369	-0.06151	-0.01242	r_s
	0.6047	0.5537	0.6853	0.5213	0.8915	P
	123	123	123	111	123	N
CHLA	0.15644	0.1566	*0.17161**	0.15875	-0.02269	r_s
	0.0669	0.0666	*0.0442*	0.0758	0.7917	P
	138	138	*138*	126	138	N
DIP	-0.14858	*-0.17211*	*-0.2064*	*-0.19851*	0.07019	r_s
	0.082	*0.0435*	*0.0151*	*0.0259*	0.4133	P
	138	*138*	*138*	*126*	138	N
DIN	*0.48438**	*0.47468**	*0.48123**	*0.48596**	0.04703	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.5839	P
	138	*138*	*138*	*126*	138	0.01365

KEY: PCT_T2 = SAVH/Tier II area*100, PCT_T3 = SAVH/Tier III area*100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV).

*Statistically significant but not in the expected direction; probably spurious (no DIN requirement).

TABLE E-3. Oligohaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the whole growing season, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Oligohaline (April-October)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	*-0.32228*	*-0.3198*	*-0.3359*	*-0.30592*	-0.03497	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.631	P
	191	*191*	*191*	*175*	191	N
PLW(1+)	*0.38378*	*0.37999*	*0.4001*	*0.36512*	0.03749	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.6154	P
	182	*182*	*182*	*166*	182	N
PLL(1+)	*0.36968*	*0.36543*	*0.38394*	*0.35327*	0.03471	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.6418	P
	182	*182*	*182*	*166*	182	N
TSS	***-0.51599***	***-0.52088***	***-0.53017***	***-0.53113***	-0.0005	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.9947	P
	182	***182***	***182***	***166***	182	N
CHLA	-0.13135	-0.12639	*-0.15859*	*-0.16549*	0.03371	r_s
	0.0701	0.0815	*0.0284*	*0.0286*	0.6434	P
	191	191	*191*	*175*	191	N
DIP	-0.14066	-0.14006	-0.12059	-0.14075	-0.05054	r_s
	0.0523	0.0533	0.0966	0.0632	0.4875	P
	191	191	191	175	191	N
DIN	0.07611	0.07199	0.1047	0.08701	-0.10422	r_s
	0.2954	0.3224	0.1495	0.2522	0.1513	P
	191	191	191	175	191	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). **Correlations in bold were significant and > +/- 0.5.**

TABLE E-4. Oligohaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the spring, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Oligohaline (April-June)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	*-0.35803*	*-0.35839*	*-0.36803*	*-0.38156*	-0.10025	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.1734	P
	186	*186*	*186*	*170*	186	N
PLW(1+)	*0.41006*	*0.40926*	*0.42278*	*0.43821*	0.09315	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.2175	P
	177	*177*	*177*	*161*	177	N
PLL(1+)	*0.41306*	*0.41214*	*0.42422*	*0.44153*	0.09762	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.1961	P
	177	*177*	*177*	*161*	177	N
TSS	*-0.46473*	*-0.46895*	*-0.46911*	*-0.47071*	-0.09005	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.2333	P
	177	*177*	*177*	*161*	177	N
CHLA	-0.03517	-0.03523	-0.06136	-0.05987	0.06745	r_s
	0.6337	0.6331	0.4054	0.438	0.3603	P
	186	186	186	170	186	N
DIP	*-0.21619*	*-0.2141*	*-0.20218*	*-0.18372*	-0.00215	r_s
	0.003	*0.0033*	*0.0056*	*0.0165*	0.9768	P
	186	*186*	*186*	*170*	186	N
DIN	0.11433	0.11214	0.13042	0.11665	-0.05129	r_s
	0.1202	0.1275	0.076	0.1298	0.4869	P
	186	186	186	170	186	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV).

TABLE E-5. Mesohaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the whole growing season, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Mesohaline (April-October)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	***-0.54526***	***-0.54944***	***-0.57505***	***-0.58657***	-0.09317	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.0872	P
	329	***329***	***338***	***309***	338	N
PLW(1+)	***0.51652***	***0.52111***	***0.55187***	***0.56544***	0.10446	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.0561	P
	326	***326***	***335***	***306***	335	N
PLL(1+)	***0.50671***	***0.51195***	***0.54913***	***0.5671***	*0.11718*	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	*0.032*	P
	326	***326***	***335***	***306***	*335*	N
TSS	*-0.21364*	*-0.22248*	*-0.2087*	*-0.20609*	-0.03407	r_s
	0.0001	*0.0001*	*0.0001*	*0.0003*	0.5343	P
	326	*326*	*335*	*306*	335	N
CHLA	*-0.36311*	*-0.36567*	*-0.35225*	*-0.33616*	-0.00415	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.9394	P
	329	*329*	*338*	*309*	338	N
DIP	*-0.3637*	*-0.37274*	*-0.41021*	*-0.41049*	-0.03386	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.535	P
	329	*329*	*338*	*309*	338	N
DIN	-0.1055	*-0.10975*	*-0.13549*	*-0.17604*	0.00965	r_s
	0.0559	*0.0467*	*0.0127*	*0.0019*	0.8596	P
	329	*329*	*338*	*309*	338	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). **Correlations in bold were significant and > +/- 0.5.**

TABLE E-6. Mesohaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the spring, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Mesohaline (April-June)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	***-0.53585***	***-0.53914***	***-0.55853***	***-0.58494***	-0.07911	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.1467	P
	329	***329***	***338***	***309***	338	N
PLW(1+)	***0.50519***	***0.50852***	***0.53784***	***0.56452***	0.08795	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.1081	P
	326	***326***	***335***	***306***	335	N
PLL(1+)	*0.49739*	***0.50187***	***0.53661***	***0.56939***	0.09797	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.0733	P
	326	***326***	***335***	***306***	335	N
TSS	*-0.22213*	*-0.23046*	*-0.2184*	*-0.21714*	-0.04769	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.3842	P
	326	*326*	*335*	*306*	335	N
CHLA	*-0.27328*	*-0.27456*	*-0.26687*	*-0.23615*	-0.01718	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.753	P
	329	*329*	*338*	*309*	338	N
DIP	*-0.27689*	*-0.28757*	*-0.32356*	*-0.31739*	-0.01924	r_s
	0.0001	*0.0001*	*0.0001*	*0.0001*	0.7245	P
	329	*329*	*338*	*309*	338	N
DIN	*-0.11043*	*-0.11041*	*-0.12817*	*-0.13662*	0.0587	r_s
	0.0453	*0.0454*	*0.0184*	*0.0163*	0.2819	P
	329	*329*	*338*	*309*	338	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations.

Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). **Correlations in bold were significant and > +/- 0.5.**

TABLE E-7. Polyhaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the whole growing season, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Polyhaline (March-May, Sept.-Nov.)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	*-0.42764*	*-0.4409*	***-0.59332***	***-0.62176***	-0.14926	r_s
	0.0007	*0.0004*	***0.0001***	***0.0001***	0.2108	P
	60	*60*	***72***	***66***	72	N
PLW(1+)	*0.39999*	*0.41133*	***0.58154***	***0.59571***	0.10555	r_s
	0.0015	*0.0011*	***0.0001***	***0.0001***	0.3845	P
	60	*60*	***70***	***64***	70	N
PLL(1+)	***0.50034***	***0.51095***	***0.65444***	***0.671***	0.15915	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.1882	P
	60	***60***	***70***	***64***	70	N
TSS	0.13456	0.1296	0.01667	-0.00031	0.07685	r_s
	0.3054	0.3237	0.8911	0.9981	0.5272	P
	60	60	70	64	70	N
CHLA	-0.03031	-0.02187	0.09341	0.14063	0.21089	r_s
	0.8181	0.8683	0.4351	0.2601	0.0754	P
	60	60	72	66	72	N
DIP	***-0.76875***	***-0.77338***	***-0.84381***	***-0.83783***	-0.11284	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.3453	P
	60	***60***	***72***	***66***	72	N
DIN	***-0.6857***	***-0.68645***	***-0.77671***	***-0.81424***	*-0.32777*	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	*0.0049*	P
	60	***60***	***72***	***66***	*72*	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). **Correlations in bold were significant and > +/- 0.5.**

TABLE E-8. Polyhaline Spearman rank correlations between water quality from Chesapeake Bay Program midchannel water quality stations over the spring, and measures of SAV area over Chesapeake Bay Program segments, adding half tidal range for PLW and PLL.

Parameter	Polyhaline (March-May)					KEY
	PCT_T2	PCT_T3	SAVH	LAGSAVH	CHGSAVH	
K_d	*-0.48878*	*-0.49618*	***-0.56852***	***-0.61765***	-0.0433	r_s
	0.0001	*0.0001*	***0.0001***	***0.0001***	0.718	P
	60	*60*	***72***	***66***	72	N
PLW(1+)	*0.40515*	*0.40959*	***0.50063***	***0.54172***	0.0179	r_s
	0.0013	*0.0012*	***0.0001***	***0.0001***	0.8839	P
	60	*60*	***69***	***63***	69	N
PLL(1+)	*0.47708*	*0.48209*	***0.57068***	***0.6122***	0.05376	r_s
	0.0001	*0.0001*	***0.0001***	***0.0001***	0.6608	P
	60	*60*	***69***	***63***	69	N
TSS	-0.14236	-0.14853	-0.20028	-0.14948	0.09456	r_s
	0.2779	0.2574	0.0989	0.2423	0.4396	P
	60	60	69	63	69	N
CHLA	-0.22172	-0.21318	-0.23034	*-0.24705*	0.003	r_s
	0.0915	0.105	0.0551	*0.0491*	0.9803	P
	59	59	70	*64*	70	N
DIP	***-0.63264***	***-0.63744***	***-0.65205***	***-0.60465***	0.00106	r_s
	0.0001	***0.0001***	***0.0001***	***0.0001***	0.9929	P
	60	***60***	***72***	***66***	72	N
DIN	-0.2457	-0.24253	*-0.34673*	*-0.43067*	*-0.31952*	r_s
	0.0585	0.0619	*0.0028*	*0.0003*	*0.0062*	P
	60	60	*72*	*66*	*72*	N

KEY: PCT_T2 = SAVH/Tier II area * 100, PCT_T3 = SAVH/Tier III area * 100, SAVH = SAV hectares for same year as water quality data; LAGSAVH = SAV hectares for following year; CHGSAVH = change in SAV hectares from that year to next; K_d = light attenuation; PLW = percent light through water column; PLL = percent light at the leaf; TSS = total suspended solids; CHLA = chlorophyll *a*; DIP = dissolved inorganic phosphorus; DIN = dissolved inorganic nitrogen; r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative for all parameters (more pollution, less SAV) except PLL/PLW (more light, more SAV). **Correlations in bold were significant and > +/- 0.5.**

TABLE E-9. Spearman rank correlations between water quality over the whole growing season and eighted mean SAV depth and percent of SAV in depth categories for tidal fresh salinity regime, using Z = 1 + half tidal range.

Parameter	Tidal fresh (April-October)					KEY
	SAVDEP	**PCT05**	**PCT1**	**PCT2**	**PCTGT2**	
K_d	*-0.47626*	*0.47844*	***-0.58376***	*-0.42696*	*-0.42813*	r_s
	0.0004	*0.0004*	***0.0001***	*0.0018*	*0.0017*	P
	51	*51*	***51***	*51*	*51*	N
PLW(1+)	*0.49962*	*-0.48311*	***0.56117***	*0.46107*	*0.44245*	r_s
	0.0002	*0.0003*	***0.0001***	*0.0007*	*0.0011*	P
	51	*51*	***51***	*51*	*51*	N
PLL(1+)	***0.50518***	*-0.48792*	***0.55483***	*0.46906*	*0.4318*	r_s
	0.0002	*0.0003*	***0.0001***	*0.0005*	*0.0016*	P
	51	*51*	***51***	*51*	*51*	N
TSS	*-0.38127*	*0.40659*	*-0.53772*	*-0.32953*	*-0.27687*	r_s
	0.0058	*0.0031*	*0.0001*	*0.0182*	*0.0492*	P
	51	*51*	*51*	*51*	*51*	N
CHLA	-0.21739	*0.31774*	***-0.62429***	-0.15157	-0.08892	r_s
	0.1254	*0.0231*	***0.0001***	0.2883	0.5349	P
	51	*51*	***51***	51	51	N
DIP	0.01297	-0.1085	0.22781	-0.05524	-0.15452	r_s
	0.928	0.4485	0.1079	0.7002	0.279	P
	51	51	51	51	51	N
DIN	0.42068*	-0.45362*	0.57813*	0.36986*	0.43815*	r_s
	0.0021	0.0008	0.0001	0.0076	0.0013	P
	51	51	51	51	51	N

KEY: SAVDEP = weighted mean overall depth, PCT05 = % in water < 0.5 m deep, PCT1 = % in water 0.5-1 m deep, PCT2 = % in water 1-2 m deep, PCTGT2 = % in water > 2 m deep, K_d = light attenuation, PLW = percent light through water column, PLL = percent light at the leaf, TSS = total suspended solids, CHLA = chlorophyll *a*, DIP = dissolved inorganic phosphorus, DIN = dissolved inorganic nitrogen, r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. * Spurious correlations (significant but not in the expected direction). Expected correlations: Negative with all parameters except positive for PLL and PLW; opposite for PCT05, since worse water quality should yield more SAV in the shallowest category, because it can't grow in deeper water. **Correlations in bold were significant and > +/- 0.5.**

TABLE E-10. Spearman rank correlations between water quality over the whole growing season and weighted mean SAV depth and percent of SAV in depth categories for oligohaline salinity regime, using Z = 1 + half tidal range.

Parameter	Oligohaline (April-October)					KEY
	SAVDEP	PCT05	PCT1	PCT2	PCTGT2	
K_d	*-0.35629*	*0.35745*	*-0.27214*	*-0.38803*	*-0.28371*	r_s
	0.0011	*0.0011*	*0.014*	*0.0003*	*0.0103*	P
	81	*81*	*81*	*81*	*81*	N
PLW(1+)	*0.42664*	*-0.4328*	*0.36788*	*0.45601*	*0.35704*	r_s
	0.0001	*0.0001*	*0.0008*	*0.0001*	*0.0011*	P
	80	*80*	*80*	*80*	*80*	N
PLL(1+)	*0.40273*	*-0.40895*	*0.3568*	*0.43501*	*0.3061*	r_s
	0.0002	*0.0002*	*0.0012*	*0.0001*	*0.0058*	P
	80	*80*	*80*	*80*	*80*	N
TSS	*-0.31315*	*0.31859*	*-0.27976*	*-0.34897*	*-0.26981*	r_s
	0.0047	*0.004*	*0.012*	*0.0015*	*0.0155*	P
	80	*80*	*80*	*80*	*80*	N
CHLA	*-0.44713*	*0.45038*	*-0.354*	*-0.46935*	*-0.37281*	r_s
	0.0001	*0.0001*	*0.0012*	*0.0001*	*0.0006*	P
	81	*81*	*81*	*81*	*81*	N
DIP	0.27848*	-0.28978*	0.27651*	0.26846*	0.46319*	r_s
	0.0118	0.0087	0.0125	0.0154	0.0001	P
	81	81	81	81	81	N
DIN	0.50124*	-0.51739*	0.47143*	0.46858*	0.34033*	r_s
	0.0001	0.0001	0.0001	0.0001	0.0019	P
	81	81	81	81	81	N

KEY: SAVDEP = weighted mean overall depth, PCT05 = % in water < 0.5 m deep, PCT1=% in water 0.5-1 m deep, PCT2 = % in water 1-2 m deep, PCTGT2 = % in water > 2 m deep, K_d = light attenuation, PLW = percent light through water column, PLL = percent light at the leaf, TSS = total suspended solids, CHLA = chlorophyll *a*, DIP = dissolved inorganic phosphorus, DIN = dissolved inorganic nitrogen, r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. * Spurious correlations (significant but not in the expected direction). Expected correlations: Negative with all parameters except positive for PLL and PLW; opposite for PCT05, since worse water quality should yield more SAV in the shallowest category, because it can't grow in deeper water.

TABLE E-11. Spearman rank correlations between water quality over the whole growing season and weighted mean SAV depth and percent of SAV in depth categories for mesohaline salinity regime, using Z = 1 + half tidal range.

Parameter	**Mesohaline (April-October)**					**KEY**
	SAVDEP	**PCT05**	**PCT1**	**PCT2**	**PCTGT2**	
K_d	-0.10712	0.0374	0.02493	_-0.33465_	_-0.33469_	r_s
	0.1361	0.6037	0.7294	_0.0001_	_0.0001_	P
	195	195	195	_195_	_195_	N
PLW(1+)	0.0638	0.00419	-0.0649	_0.29527_	_0.34068_	r_s
	0.3755	0.9536	0.3674	_0.0001_	_0.0001_	P
	195	195	195	_195_	_195_	N
PLL(1+)	0.06224	0.00508	-0.06511	_0.29925_	_0.33304_	r_s
	0.3873	0.9438	0.3658	_0.0001_	_0.0001_	P
	195	195	195	_195_	_195_	N
TSS	_0.25752*_	_-0.30892*_	_0.36127*_	0.01639	-0.04042	r_s
	_0.0003_	_0.0001_	_0.0001_	0.8201	0.5748	P
	_195_	_195_	_195_	195	195	N
CHLA	_-0.18377_	_0.16851_	_-0.15538_	_-0.20927_	-0.12626	r_s
	_0.0101_	_0.0185_	_0.0301_	_0.0033_	0.0786	P
	_195_	_195_	_195_	_195_	195	N
DIP	_-0.18847_	_0.2013_	_-0.23045_	_-0.1571_	-0.07433	r_s
	_0.0083_	_0.0048_	_0.0012_	_0.0283_	0.3018	P
	_195_	_195_	_195_	_195_	195	N
DIN	_-0.28457_	_0.30415_	_-0.32576_	_-0.1818_	_-0.20125_	r_s
	_0.0001_	_0.0001_	_0.0001_	_0.011_	_0.0048_	P
	_195_	_195_	_195_	_195_	_195_	N

KEY: SAVDEP = weighted mean overall depth, PCT05 = % in water < 0.5 m deep, PCT1 = % in water 0.5-1 m deep, PCT2 = % in water 1-2 m deep, PCTGT2 = % in water > 2 m deep, r_s = Spearman rank correlation coefficient, P = statistical probability (_significant shown in italics if P < 0.05_) and N = sample size, number of segment-year combinations. * Spurious correlations (significant but not in the expected direction). Expected correlations: Negative with all parameters except positive for PLL and PLW; opposite for PCT05, since worse water quality should yield more SAV in the shallowest category, because it can't grow in deeper water.

TABLE E-12. Spearman rank correlations between water quality over the whole growing season and weighted mean SAV depth and percent of SAV in depth categories for polyhaline salinity regime, using Z = 1 + half tidal range.

Parameter	Polyhaline (March-May, September-November)					KEY
	SAVDEP	PCT05	PCT1	PCT2	PCTGT2	
K_d	*-0.40593*	*0.46252*	*-0.49876*	-0.20957	*-0.31768*	r_s
	0.0026	*0.0005*	*0.0001*	0.132	*0.0205*	P
	53	*53*	*53*	53	*53*	N
PLW(1+)	*0.39089*	*-0.46275*	***0.52564***	0.20059	0.21888	r_s
	0.0038	*0.0005*	***0.0001***	0.1498	0.1153	P
	53	*53*	***53***	53	53	N
PLL(1+)	*0.45614*	***-0.51691***	***0.57619***	0.24712	*0.27536*	r_s
	0.0006	***0.0001***	***0.0001***	0.0744	*0.046*	P
	53	***53***	***53***	53	*53*	N
TSS	-0.04574	0.09946	-0.15047	-0.05782	0.0346	r_s
	0.745	0.4786	0.2822	0.6809	0.8057	P
	53	53	53	53	53	N
CHLA	-0.22067	0.24866	-0.22397	-0.23647	-0.0341	r_s
	0.1123	0.0726	0.1069	0.0882	0.8085	P
	53	53	53	53	53	N
DIP	***-0.54431***	*0.49792*	*-0.48986*	*-0.42408*	***-0.60252***	r_s
	0.0001	*0.0001*	*0.0002*	*0.0016*	***0.0001***	P
	53	*53*	*53*	*53*	***53***	N
DIN	***-0.58385***	*0.49099*	*-0.42222*	***-0.55344***	*-0.55444*	r_s
	0.0001	*0.0002*	*0.0016*	***0.0001***	*0.0001*	P
	53	*53*	*53*	***53***	*53*	N

KEY: SAVDEP = weighted mean overall depth, PCT05 = % in water < 0.5 m deep, PCT1 = % in water 0.5-1 m deep, PCT2 = % in water 1-2 m deep, PCTGT2=% in water > 2 m deep, K_d = light attenuation, PLW = percent light through water column, PLL = percent light at the leaf, TSS = total suspended solids, CHLA = chlorophyll *a*, DIP = dissolved inorganic phosphorus, DIN = dissolved inorganic nitrogen, r_s = Spearman rank correlation coefficient, P = statistical probability (*significant shown in italics if P < 0.05*) and N = sample size, number of segment-year combinations. Expected correlations: Negative with all parameters except positive for PLL and PLW; opposite for PCT05, since worse water quality should yield more SAV in the shallowest category, because it can't grow in deeper water. **Correlations in bold were significant and > +/- 0.5.**